ECONOMIC GEOLOGY

VOL. XXIX SEPTEMBER–OCTOBER, 1934 No. 6

PROGRESSIVE REGIONAL METAMORPHISM OF THE LOWER KITTANNING COAL BED OF WESTERN PENNSYLVANIA.[1]

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INTRODUCTION.

ALL early interpretations of the changes undergone by the original ingredient plant matter in its transformation from peat to coal were connected with the early attempts at the classification of coal. The differences between lignites, bituminous coals, and anthracites were attributed to differences in the original vegetable matter produced in various geologic epochs, or to the time elapsed since deposition. The brown coals and lignites ("younger" coals) were regarded as Mesozoic and Tertiary, and all bituminous and anthracite coals were thought to be Paleozoic in age. The origin of the idea that the character of a coal is dependent on its age lies in the fact that in western Europe, where coals were first studied, most of the bituminous and anthracitic coal fields are found in Paleozoic rocks, whereas brown coals and lignites occur in formations of later ages. This conception has been so deep-seated that until lately the coal tariffs of many large coal-producing countries, including the United States, were based on the age of the coal.

The more extensive examination of the coal fields throughout the world, however, brought out the fact of the existence of

[1] Presented before Society of Economic Geologists, Princeton meeting, July, 1933. Published by permission of the Director of the U. S. Geological Survey.

typical brown coals in formations of lower Carboniferous age (Moscow and Ukraine coal basins) and revealed that bituminous, semibituminous, and anthracitic coals not uncommonly occur in formations of Mesozoic and Tertiary age (Canada, United States,

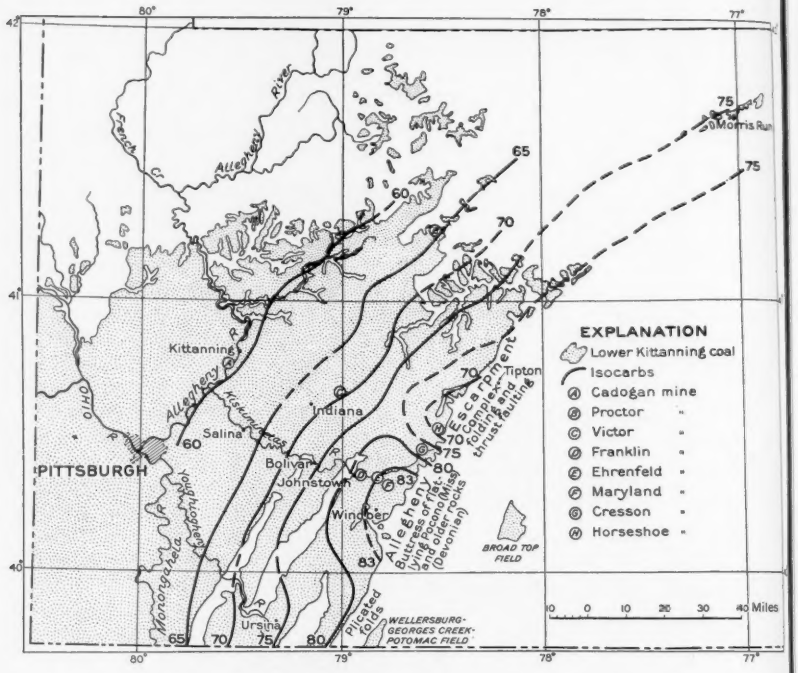


FIG. 1. Map of western Pennsylvania, showing progressive carbonization of the Lower Kittanning coal (based on about 2,000 proximate analyses). Fixed carbon (pure coal basis) percentage in the Lower Kittanning coal. Samples for special study were collected at the following localities: Cadogan mine, North Buffalo, Armstrong County (*A*); Proctor mine, Force, Elk County (*B*); Victor mine, Clymer, Indiana County (*C*); Franklin mine, near Johnstown (*D*); Ehrenfeld mine, near South Fork (*E*); Maryland shaft, at St. Michael (*F*); Cresson mine, at Cresson (*G*); the last four are in Cambria County. Analyses of the same bed mined at Horseshoe mine, Coupon, Blair County (*H*) are quoted for comparison.

Alaska, Siberia, Island of Sakhalin, etc.) Therefore, the idea that differences in age are an explanation of the various ranks of coal has been abandoned by most geologists.

In the course of the last 10 or 15 years, in connection with researches based on coal distillation and hydrogenation on the one hand, or on the microscopy and field studies of coal on the other, a number of theories attempting to explain the processes of carbonization have been brought forth. These theories may be divided into three classes:—(1) physico-chemical, (2) biochemical, and (3) geologic. For the most part they present elaborations, modifications, or combinations of theories promulgated from 20 to one hundred years ago. Only the most outstanding of the biochemical and geologic theories will be discussed in this paper.

Scope of Study and Region Selected.

This paper is a preliminary report of progress of studies, the object of which was in part to gain further knowledge of the progressive metamorphism of coals on a regional scale and especially to determine the changes in the physical character and chemical composition of the principal components of ordinary banded coals as the carbonization of the organic matter goes forward in the natural process from rank to rank.

For this investigation a single bed, the Lower Kittanning coal, was chosen in the northern Appalachian Trough, an unrivaled region for the observation of the progressive metamorphism, as coals pass nearly horizontally and almost without folding from one side to the other of a great syncline. The bed selected is one of the most regularly bedded, widely distributed, extensively mined, and persistent coal beds of western Pennsylvania.[2] It lies less than 30 feet above the Vanport limestone and about 115

[2] The areal geology of the region, and the columnar sections, including the Lower Kittanning coal, with local details of the stratigraphy, may be found in the following publications: U. S. Geol. Survey folios Nos. 102, 115, 123, 125, 133, 174, 189; Reports of Progress and Annual Reports, Second Geol. Survey of Penn.; James D. Sisler: Bituminous Coal Fields of Pennsylvania. Bull. M-6, Penn. Top and Geol. Survey, 1932, 2d ed.

feet above the base of the Allegheny formation, Pennsylvanian series. It corresponds approximately to the lower boundary of the Stephanian in Europe. The Vanport limestone is marine. Another marine horizon, the Johnstown limestone ("cement bed"), occurs about 80 feet above the Lower Kittanning coal.

SAMPLING THE LOWER KITTANNING BED.

The bed was sampled by taking columnar and channel samples at the following mines: (*A*) Cadogan mine, North Buffalo, Armstrong County; (*B*) Proctor mine, Force, Elk County; (*C*) Victor mine, Clymer, Indiana County; (*D*) Franklin mine, near Johnstown; (*E*) Ehrenfeld mine, near South Fork; (*F*) Maryland shaft, at St. Michael, and (*G*) Cresson mine, at Cresson, the

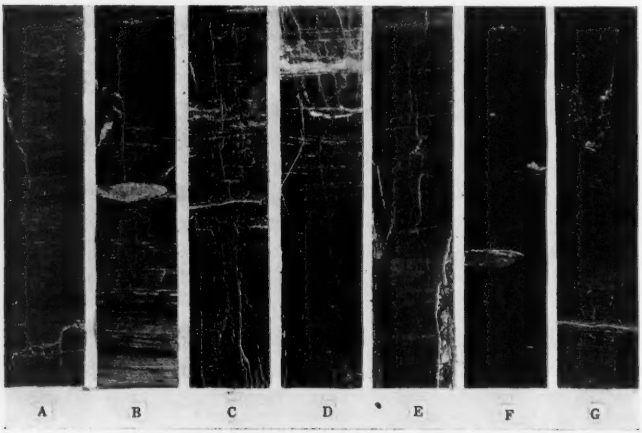


FIG. 2. Lower Kittanning coal. Portions of the columnar sections, polished to show macro-structure. *A*—Cadogan mine; *B*—Proctor mine; *C*—Victor mine; *D*—Franklin mine; *E*—Ehrenfeld mine; *F*—Maryland shaft; *G*—Cresson mine. The jet black ("bright") bands represent highly toxic conditions of deposition. The gray bands in most samples are largely composed of fine shreds of "wood," with some spores, cuticles, resins, and waxes. Note white lenticles and lenses of pyrites and gray fusain.

last four being in Cambria County. The locations of these mines, and isocarbs representing the regional metamorphism of the coal bed from the Allegheny River to the eastern part of Cambria County, near the Allegheny Escarpment in Pennsylvania, are shown in Fig. 1. In addition to the seven mines sampled, analyses of coal from Horseshoe mine, Coupon, Blair County (*H*) are quoted for comparison.

The columnar samples were cut from fresh faces. As the Lower Kittanning bed, particularly east of Indiana County, is highly jointed and exceedingly friable, the cutting of the samples required careful manipulation. A pillar or column about one foot square was cut with a geological pick by first making narrow channels at the top of the bed and on two sides. When the pillar was cut around for a foot or so, the cut-out part was wrapped in sheet lead and secured with insulating tape. The process was continued until a complete column was cut out and wrapped in lead; then it was shrouded in burlap, tied with rope, and pried out at top and bottom. In most cases the columns broke out in clean-cut, even surfaces. After removal from the mines they were carefully packed and shipped to Washington, D. C.

The standard or "channel" samples were taken in all but the Ehrenfeld mine and the Cresson mine No. 9 (Pennsylvania Coal & Coke Co., Cresson, Pa.). These samples were crushed in the mine to pass through one-inch mesh, quartered, placed in standard sampling cans, and submitted for proximate and ultimate analysis to the U. S. Bureau of Mines Experiment Station in Pittsburgh, Pa.

Average samples taken from all columnar samples were also analyzed for comparison.

General Characteristics of the Columnar Samples.

All columnar samples were carefully unwrapped in Washington and their general characteristics noted. It was observed that after being uncovered the columns that had previously been intact developed vertical cracks and horizontal splits, thus yielding several blocks. The splitting of the column seldom took place

in the bright coal, but occurred mostly along a pyrite layer, fusain (mineral charcoal), or shaly parting between the laminae.

In all the mines examined it was noted that generally the coal lying immediately below the roof and above the floor is considerably more friable than that in the center of the bed. At the top and bottom the jointing is more highly developed, and in many instances the blocks will break into small pieces from 2 to 3 inches long and only half an inch in diameter. In the central part of the coal bed in most mines, blocks 12 to 17 inches long and 8 to 10 inches in diameter are formed, and the coal in these blocks is considerably stronger than that above or below.

The physical characteristics of the coal bed as sampled at different mines change from mine to mine. Thus, the coal at the Cadogan mine (at the Allegheny River, Armstrong County) is rather hard and tough. In the Proctor mine, also, it is hard and blocky, but at the Victor mine, particularly at the base and at the top, it becomes more friable and shows some effects of compression.

The most pronounced effect of pressure is observed in the Johnstown area, in the Franklin and Ehrenfeld mines, where the top and bottom of the coal breaks readily into small pieces that show birdseye structure. In these mines, cone-in-cone structure parallel to the bedding planes, so splendidly developed in some of the western coals (Coryell mine, Colorado, and Teton mine, Idaho), is evident. The central parts of the columns show the effects of horizontal pressure in the development of slickenside surfaces, angular slipping, and the formation of flat trapezoid pieces with highly polished surfaces.

The column of coal from the Maryland shaft, after being opened in the laboratory, split into three large blocks, 10, 12¾, and 10¾ inches high. The coal at the top and the bottom, particularly at the extreme ends, was very friable and showed numerous fine joint planes. The central block is considerably stronger, and some force was required to divide it into smaller parts at the time of preparation for polishing. This column, although highly jointed, does not exhibit the trapezoid slipping mentioned above.

At Cresson, also, the effect of pressure is quite apparent. In a block 4 inches high immediately above the floor, slickenside and curved surfaces suggest buckling of the coal material.

MACROSCOPIC AND CHEMICAL CHARACTERISTICS OF THE LOWER KITTANNING COAL BED.

The Lower Kittanning coal is a bituminous coal of the banded type. The character and distribution of the bands or laminae through the whole extent of the bed from east to west are not uniform, but differ in different mines. A detailed description of the deposit as revealed by successive laminae will be given in a later publication; only the general features will be presented here.

The Cadogan coal is characterized by fine lamination, most of the layers averaging about 0.5 mm. in thickness although many bands are only 0.03 to 0.05 mm. thick. Only rarely do some of the bright bands reach 8 mm. or even 1 cm. in thickness. The amount of fusain is not great, but pyrite is present as fine grains scattered throughout the bed and also as large inclusions.

In the Proctor mine near Force, Elk County, the coal at the top and bottom of the bed is high in ash and may be regarded as "bony" coal. It is finely laminated and contains lenses as well as fine laminae of fusain and pyrite. The pure bright bands are not thick nor numerous.

In addition to the ordinary dull variety of coal, layers of gray coal with a distinctly granular structure are noted in all the remaining mines. On polishing, the granular structure becomes almost obliterated to the naked eye, but can be detected under the microscope.

The bright bands of the Victor coal, although not numerous, in several instances exceed 15 mm. in thickness. Small grains of pyrite in parallel lines are rather characteristic in several parts of the bed (46 inches thick).

The distinction between the bright and dull or gray-granular bands in coals from the Maryland shaft and the Ehrenfeld and Franklin mines in Cambria County is not so striking as in the mines described above. Coal from these mines, particularly when

highly polished, appears quite bright and black. The laminae or bands in a considerable part of the coal in the Maryland shaft and the Franklin mine are rather broad and commonly reach one centimeter or more in thickness. In the Ehrenfeld mine, however, the lamination is very fine, and throughout the whole thickness of the sample only a few bands are 8–10 mm. thick.

According to David White,[3] the laminae are "climatic records, dominantly seasonal—varves, in effect." They show the changes that took place in the environmental conditions in peat-forming swamps at the time of deposition, and indicate fluctuations (1) of the rainfall, which controls the water level, (2) of the temperature, affecting the rate of growth and decay of plants as well as the water level, and (3) of the degree of toxicity.

The character of the banding can be well observed in the polished surfaces of coal. In the photographs all laminae high in ash content appear very light, almost white; pyrite and fusain also photograph much lighter than the bright coal (Fig. 2).

Since the publication by Dr. Stopes of her paper "On the Four Visible Ingredients in Banded Bituminous Coal,"[4] an extensive literature has grown up on the subject of the microstructure, chemical composition, and origin of the various bands.

Unfortunately, Dr. Stope's classification, admirable from the philological point of view, is at present in a state of confusion.[5] Nearly every follower of this classification, in adopting the terminology has changed it to suit himself, modifying definitions and introducing subclasses. These changes are partly a result of improved technique in the study of the microstructure of coal and the consequent better understanding of the true character of its composition.

[3] White, David: Rôle of the Water Conditions in the Formation and Differentiation of Common (banded) Coals. ECON. GEOL., vol. 26, no. 6, pp. 556–570, 1933.

[4] Stopes, Marie C.: On the Four Visible Ingredients in Banded Bituminous Coal —Studies in the Composition of Coal, No. 1. Proc. Roy. Soc., vol. 90, pp. 470–487, 2 pls., London, 1919.

[5] *Note.*—The confusion that exists has been discussed by C. A. Seyler, who urges "a symposium between those interested in the subject in order to settle the terminology."

The original definition of bright coal (vitrain), as uniform and structureless—as a "hardened glue or jelly"—obviously can not be maintained, for beautiful preservation of fine cell structure is constantly demonstrated in the most typical vitrains.[6]

The well known classification of Thiessen,[7] used by the U. S. Bureau of Mines and a number of writers in this country as well as in Europe, has been notably modified and elaborated in the last 3 or 4 years. Opaque and translucent "attritus," "splint," and "semi-splint" and the "An-At" (anthraxylon-attritus) and "At-An" (attritus-anthraxylon), depending on the ratio of "pure" attritus to anthraxylon present in a band, have been added to the original terms, anthraxylon and attritus.

It appears to the writer that, although microscopic examinations have contributed greatly to our knowledge of the constitution of coal, the development of elaborate classifications, often based on insufficient observations or imperfect technique, has hindered our progress in the better understanding of the origin and composition of coal. In the present paper, therefore, old or merely descriptive terms are used, such as "bright" coal, "gray granular," or "dull," "micro-debris," "groundmass," etc., as it is believed that they convey a clearer meaning and will not be misunderstood or misinterpreted by readers not versed in the intricacies of the classifications referred to above.

Separation of the Various Components.

"Bright" Coal (anthraxylon-attritus vitrain).—The matter composing the bright bands, although quite friable, can be separated without much difficulty with the aid of an $\times 7$ lens and such simple implements as a coarse needle and a pocket knife. It is recovered in a rather pure state as angular or prismatic grains of variable size.

6 Hickling, H. G. A.: The Microstructure of the Coal in Certain Fossil Trees. Trans. Inst. Min. Eng., vol. 84, part 2, pp. 13–29, London, 1932.

7 Thiessen, Reinhardt, and Francis, Wilfrid: Terminology in Coal Research. U. S. Bur. Mines Tech. Paper 446, 1929. Thiessen, Reinhardt, and others: Microscopic Study of Elkhorn Coal Bed, Letcher County, Kentucky. U. S. Bur. Mines Tech. Paper 506, 1931.

Fusain ("mother of coal" or mineral charcoal), although not uniform in its physical properties, can as a rule also be obtained free from other components in amounts sufficient for chemical analysis. Pure fusain crushes readily into fine powder between the fingers. It has been pointed out that fusain is mainly responsible for soiling the hands in the handling of coal and is found in large proportion in the mine dust. The harder varieties of fusain contain large amounts of ash and commonly are infiltrated with pyrite.

Dull Coal (micro-debris, durain, clarain—in part, attritus).—Separation of the duller or gray bands in a pure state is almost impossible, as these bands always contain as inclusions fine laminae or lenses of bright coal or fusain, or both.

Chemical Analyses of the Components of the Bed.

Samples of coal from typical bands in each columnar sample have been extracted and analyzed at the Experiment Station of the U. S. Bureau of Mines at Pittsburgh, Pa. The proximate and ultimate analyses are given in Table 1 and are illustrated by several diagrams. They show a progressive decrease in the volatile matter from 41.4 to 15.3 per cent. in the eastward direction, with one exception, namely, the Cresson mine, which is located north of the Johnstown-Windber area (Fig. 1).

There is also evident progressive increase in the carbon content, with slow loss of hydrogen and more rapid loss of oxygen.

The differences in the composition of the individual bands are not striking and appear to be erratic. Close examination shows them to correspond to the characteristics in the chemical composition of the various components. A number of diagrams (Figs. 3–7) illustrate the chemical composition of the various coal components as well as progressive evolution of the coal matter in the mines sampled.

Figure 3 shows the change in the carbonization of the bed eastward from the Allegheny River to the Allegheny Escarpment. The fixed carbon content is represented on the ordinates. The abscissas of the mines are the projection on a line drawn through

Cadogan Mine (*A*) at right angles to the isocarbs. The analyses plotted were recalculated to the "unit coal" basis,[8] where corrections for water of hydration and sulphur were introduced.

The minimum degree of carbonization of the samples collected was found at Cadogan mine, at the westernmost point in the area examined, where the fixed carbon (average of the columnar sample) is 58.6%. The maximum carbonization of the bed is found at the Maryland shaft, where the fixed carbon reaches 84.7%. A rapid decrease in the carbonization is observed at the Cresson mine, where the fixed carbon is only 76.1%, while at the Horseshoe mine[9] it drops to 65.1% and is approximately the same as at the Proctor mine, near Force, Elk County.

The degree of carbonization in the bright, dull, and gray bands selected from each columnar sample, as expressed by proximate analysis, is in most instances approximately the same.

The fixed carbon of fusain is invariably higher than in the average coal or in any other bands of coal, and varies from mine to mine. It does not quite follow the line of progressive carbonization of the average coal. Thus, in the Proctor mine the fixed carbon of fusain is only slightly lower than in the Ehrenfeld mine and almost identical with that in the Franklin mine (89.2 and 89.1), whereas the fixed carbon in the average sample from the Proctor mine is only 67% and in the Franklin and Ehrenfeld mines it is 80.9% and 81.9%, respectively. The apparent variation from the fixed carbon of the other components, or of the entire bed, is probably due to actual variation in the composition of the fusain in the early stage of coal formation.

Figure 4 represents progressive changes in the eastward direction in the composition of coal as determined by ultimate analyses. The percentages of nitrogen, hydrogen, and carbon (moisture-, ash-, sulphur-free basis) of the average coal samples and bright and fusain components as they are found from mine to mine, are plotted on the ordinates.

[8] Parr, Samuel W.: The Classification of Coal. Univ. Ill. Bull. 48, July 31, 1928.

[9] An analysis of a sample from the Horseshoe mine, quoted from Bull. M-6 (Bituminous Coal Fields of Penn., Pt. II, Penn. Geol. Survey, 1926), is given for comparison and illustration of the progressive carbonization.

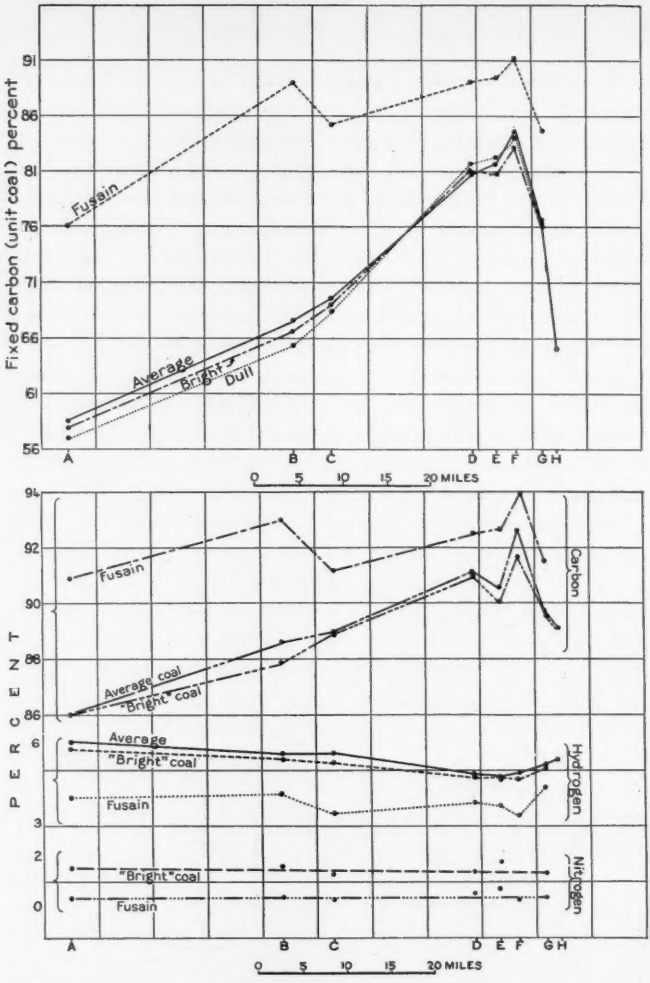


FIG. 3 (above). Progressive changes in the fixed carbon content in the Lower Kittanning coal. *A*—Cadogan mine; *B*—Proctor mine; *C*—Victor mine; *D*—Franklin mine; *E*—Ehrenfeld mine; *F*—Maryland shaft; *G*—Cresson mine; *H*—Horseshoe mine.

FIG. 4 (below). Progressive changes in the ultimate composition of the Lower Kittanning coal. *A*—Cadogan mine; *B*—Proctor mine; *C*—Victor mine; *D*—Franklin mine; *E*—Ehrenfeld mine; *F*—Maryland shaft; *G*—Cresson mine; *H*—Horseshoe mine.

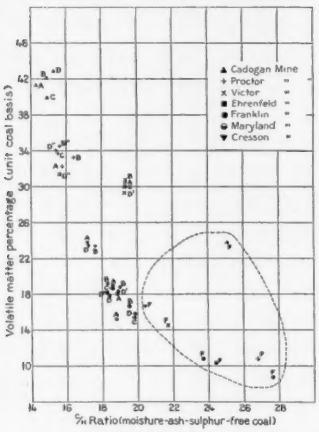
The nitrogen content is practically the same in all the mines examined, and is almost identical in bright, dull, and average coal. In fusain, however, it is considerably lower and does not exceed 0.5%, or about one-third of that in the average coal in all the mines except the Ehrenfeld, where the nitrogen content is 0.8%. A comparison of the analyses of fusain and of the dull coal from this mine shows clearly that each component has a small admixture of the other (Table I).

The changes in the hydrogen content from mine to mine indicate that in the course of the progressive carbonization of coal, a gradual elimination of hydrogen takes place. In general the amount of hydrogen is higher in the dull or gray bands and lower in the bright bands than it is in the average samples, but the differences are in some instances insignificant and may be due to experimental errors. A consideration of the chemical composition of the carbohydrates, waxes, fats, and oils may be helpful in the interpretations of the results of analysis of the various bands. The amount of hydrogen in wood averages about 6.7%; in resins, such as fossil copal, it reaches 10.8%, and in waxes is as high as 14%. Therefore, the composition of the dull coal (attritus, clarain, durain, splint, and semi-splint) consisting of a mixture of plant micro-debris, fragments of woody tissues, resins, spores, and waxes, can not be uniform.

The amount of carbon in the Lower Kittanning coal changes from west to east, ranging from 86 to 92.6% in the ordinary coal, and from 90.9 to 94% in fusain. The maximum carbon content is found in the Maryland shaft. It is important to note that in the Ehrenfeld mine, where the fixed carbon, as it is seen in Fig. 3, is similar to that in the Franklin mine, the total carbon content is distinctly lower in the average, and particularly in the bright coal. This indicates that even at a high stage of carbonization (low-volatile rank) the original differences in the chemical composition, largely due to the differences in the environmental conditions, are not completely obliterated, but can still be detected in the proximate and ultimate analyses.

Figure 5 shows the relationship between the volatile matter

(unit coal) and carbon-hydrogen ratio (moisture-, ash-, sulphur-free basis). The mines are designated by special signs and the various coal components as well as the average and channel samples are marked by letters. The relationships in all or some of the varieties of coal found in certain mines are almost identical. Fusain in all mines is characterized by low volatile matter and



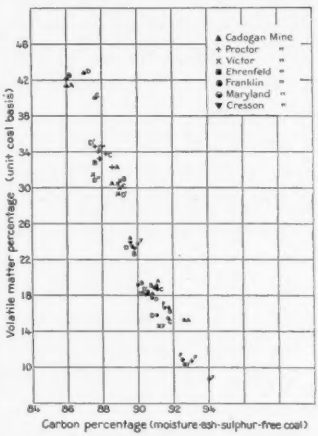


FIG. 5 (left). Changes in relation between volatile matter and C/H ratio in the Lower Kittanning coal and its macro-components. *A*—Average sample; *B*—bright coal; *C*—Channel sample (Standard); *D* and *D'*—dull or granular coal; *F*—fusain.

FIG. 6 (right). Progressive changes in the volatile matter and carbon content of the Lower Kittanning coal. *A*—Average sample; *B*—bright coal; *C*—Channel sample (Standard); *D* and *D'*—dull or granular coal; *F*—fusain.

high carbon-hydrogen ratio, due, as can be seen from the ultimate analyses, to the higher content of carbon in this component. The similarity in the chemical composition of the coal from the Franklin and Ehrenfeld mines is evident. At the same time, some of the differences point to differences in the original composition and to the fact that coal is a complex aggregate of a large number of organic compounds.

Figure 7 represents the relationship of oxygen to carbon (moisture-, ash-, sulphur-free basis). Fusain from all mines falls in a separate group. All coal components of the Proctor mine, with the exception of a "bony layer," are close in their gross chemical composition, so far as indicated by the O/C ratio.

The average sample from the Maryland shaft has an unusually low oxygen content. The explanation may lie in errors in sam-

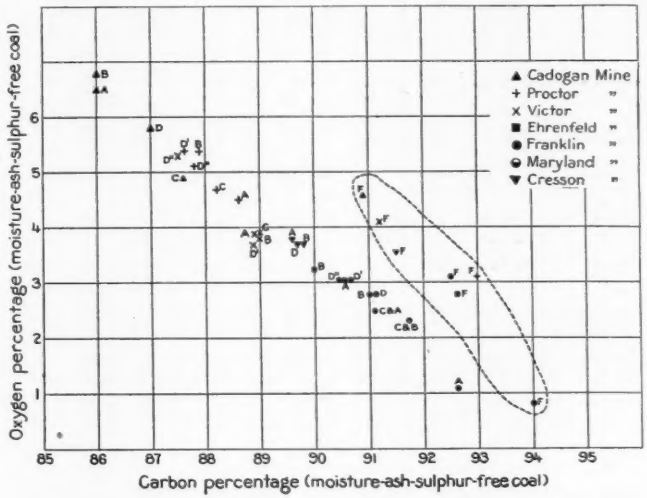


FIG. 7. Progressive elimination of oxygen in relation to total carbon in the Lower Kittanning coal. *A*—Average sample; *B*—bright coal; *C*—Channel sample (Standard); *D* and *D'*—dull or granular coal; *F*—fusain.

pling and in the fact that the oxygen has been determined by the "difference" and actually represents not only the oxygen content, but the errors of analysis as well. The channel sample from the Cadogan mine is also too low in oxygen. In this instance, in addition to ordinary errors of analysis, the error may have been increased by the presence of large amounts of pyrite (sulphur—5.9%, Table I).

Figure 6 represents the relative proportions of volatile matter to total carbon and is to some extent comparable with Fig. 5. It fails, however, to separate the fusain component of coal as it is

TABLE I.

PROXIMATE AND ULTIMATE ANALYSES OF THE LOWER KITTANNING COAL AND ITS MACRO-COMPONENTS.

	Laboratory Number		Moisture	Volatile matter	Fixed Carbon	Ash	Sulphur	Hydrogen	Carbon	Nitrogen	Oxygen	B. t. u.'s	C/N Ratio
Cadogan Mine No. 1, Armstrong County, Pa. Standard sample.	A 77860	a.	1.8	36.3	52.2	9.7	5.2	5.2	75.1	1.2	5.6	13,340	
		b.	-	41.1	58.9	-	5.9	5.6	82.6	1.4	4.5	15,070	
		c.	-	40.0	60.0	-	-	6.0	87.6	1.5	4.9	16,330	14.89
Average sample from columnar sample.	A 81055	a.	0.9	39.0	53.8	6.3	2.1	5.5	78.1	1.4	6.6	14,190	
		b.	-	42.1	57.9	-	2.3	5.8	84.2	1.5	6.2	15,290	
		c.	-	41.4	58.6	-	-	6.0	86.0	1.5	6.5	15,290	14.34
Bright coal	A 77787	a.	0.9	41.0	55.2	2.9	1.4	5.5	81.7	1.3	7.2		
		b.	-	42.6	57.4	-	1.5	5.6	84.9	1.5	6.6		
		c.	-	42.1	57.9	-	-	5.8	86.0	1.4	6.9		14.63
Dull coal.	A 77788	a.	0.7	41.1	55.7	4.5	1.9	5.2	81.0	1.4	6.0		
		b.	-	43.4	56.6	-	2.0	5.5	85.4	1.5	5.6		
		c.	-	42.8	57.2	-	-	5.7	87.0	1.5	5.8		15.3
Fusain.	A 77786	a.	.2	23.3	68.8	9.7	3.1	3.6	79.0	.4	4.2		
		b.	-	25.8	74.2	-	4.5	4.0	87.7	.4	4.5		
		c.	-	23.9	76.1	-	-	4.1	90.9	.4	4.6		29.18
Proctor Mine No. 9, Elk County, Pa. Standard sample.	A 77862	a.	1.4	32.4	60.9	5.3	1.9	5.3	80.6	1.3	5.6	14,430	
		b.	-	34.7	65.3	-	2.1	5.5	85.4	1.4	4.6	15,480	
		c.	-	35.8	66.2	-	-	5.7	88.2	1.4	4.7	15,610	15.48
Average sample, taken from columnar sample.	A 81057	a.	0.7	31.4	63.4	4.5	2.0	5.2	82.3	1.2	4.8	14,860	
		b.	-	33.1	66.9	-	2.1	5.4	86.8	1.3	4.4	15,470	
		c.	-	32.3	67.7	-	-	5.6	88.6	1.3	4.5	15,600	15.82
Bright coal.	A 81058	a.	.7	32.9	64.9	1.5	.7	5.3	85.4	1.3	5.8	15,150	
		b.	-	33.6	66.4	-	-	5.4	87.2	1.3	5.4	15,480	
		c.	-	33.3	66.7	-	-	5.4	87.9	1.3	5.4	15,580	16.47
Dull gray coal.	A 81059	a.	0.7	32.9	61.0	5.4	1.4	5.2	81.1	1.3	5.6	14,550	
		b.	-	35.0	65.0	-	1.5	5.2	86.3	1.4	5.3	15,480	
		c.	-	34.6	65.4	-	-	5.6	87.6	1.4	5.4	15,610	15.67
Granular gray.	A 81060	a.	0.4	32.6	62.7	4.3	.8	5.4	82.8	1.3	5.4		
		b.	-	34.2	65.8	-	.9	5.6	87.0	1.4	5.1		
		c.	-	34.0	66.0	-	-	5.7	87.8	1.4	5.1		15.40
Fusain.	A 81487	a.	0.7	11.5	77.8	10.0	3.1	3.1	80.2	.3	5.3		
		c.	-	10.8	89.2	-	-	3.5	93.0	.4	3.1		28.80
Victor Mine No. 29, Clymer, Indiana County, Pa. Standard sample.	A 77861	a.	1.2	28.5	63.9	6.6	1.6	5.2	80.5	1.4	4.7	14,390	
		b.	-	30.7	69.3	-	1.8	5.5	87.4	1.5	3.8	15,610	
		c.	-	30.0	70.0	-	-	5.6	89.0	1.5	3.9	15,750	19.32
Average sample from columnar sample.	A 81056	a.	.6	29.1	64.8	5.5	1.8	5.2	81.9	1.5	4.1	14,710	
		b.	-	31.0	69.0	-	1.9	5.5	87.2	1.6	3.8	15,660	
		c.	-	30.5	69.5	-	-	5.6	88.9	1.6	3.9	15,920	19.80
Bright coal.	A 79677	a.	.4	30.0	67.0	2.6	.8	5.3	85.5	1.5	4.2	15,220	
		b.	-	30.9	69.1	-	.9	5.5	88.2	1.5	3.8	15,680	
		c.	-	30.8	69.2	-	-	5.6	89.0	1.6	3.6	15,750	19.30
Granular gray.	A 79676	a.	.4	27.9	65.0	6.7	.8	5.2	81.9	1.5	3.9	14,480	
		b.	-	30.0	70.0	-	.9	5.6	88.1	1.7	3.7	15,580	
		c.	-	29.4	70.6	-	-	5.7	88.9	1.7	3.7	15,720	19.30
Dull coal.	A 79678	a.	.3	25.1	52.6	22.0	1.5	4.3	66.8	1.1	4.3	11,610	
		b.	-	32.3	67.7	-	1.9	5.5	85.9	1.5	3.2	14,930	
		c.	-	31.5	68.5	-	-	5.6	87.5	1.6	3.3	15,550	15.62
Fusain.	A 81488	a.	.7	14.9	75.2	9.2	2.6	3.7	79.9	.5	4.1		
		b.	-	16.5	83.5	-	2.9	4.0	88.7	.5	3.9		
		c.	-	14.6	85.4	-	-	4.2	91.2	.5	4.1		21.68

	Laboratory Number		Moisture	Volatile matter	Fixed Carbon	Ash	Sulphur	Hydrogen	Carbon	Nitrogen	Oxygen	B. t. u.'s	C/N ratio
Cresson Mine No. 9 B, Cresson, Cambria County, Pa. Average columnar sample.	A 81475	a.	.6	22.5	70.4	6.5	.6	4.9	82.6	1.3	4.1	14,920	
		b.	-	24.2	75.8	-	.7	5.2	88.9	1.4	3.8	15,650	
		c.	-	23.9	76.1	-	-	5.2	89.6	1.4	3.8	15,750	17.21
Bright.	A 81476	a.	.5	22.9	73.8	2.8	.5	5.0	86.5	1.4	4.0		
		b.	-	23.7	76.3	-	.5	5.1	89.5	1.4	3.7		
		c.	-	23.4	76.6	-	-	5.1	89.9	1.4	3.7		17.60
Granular gray.	A 81477	a.	.6	22.1	68.0	9.3	.4	4.7	80.4	1.3	3.9		
		b.	-	24.6	75.4	-	.4	5.2	89.3	1.4	3.7		
		c.	-	23.6	76.4	-	-	5.2	89.7	1.4	3.7		17.25
Fusain.	A 81478	a.	.6	16.7	76.0	6.7	1.7	4.0	83.3	.5	3.8		
		b.	-	18.1	81.9	-	1.8	4.3	89.8	.5	3.6		
		c.	-	16.7	83.3	-	-	4.4	91.5	.5	3.6		20.4
Ehrenfeld Mine, Cambria County, Pa. Average sample.	A 89579	a.	.7	17.6	77.1	4.6	.6	4.6	85.5	1.5	3.4	14,820	
		b.	-	18.6	81.4	-	.6	4.7	90.0	1.6	3.1	15,640	
		c.	-	18.1	81.9	-	-	4.8	90.6	1.6	3.1	15,730	18.8
Bright coal.	A 89580	a.	.7	19.0	78.6	1.7	.5	4.7	87.4	1.6	4.1	15,450	
		b.	-	19.4	80.6	-	.5	4.8	89.5	1.6	3.5	15,800	
		c.	-	19.2	80.8	-	-	4.9	89.9	1.6	3.5	15,850	19.3
Duller gray coal.	A 89581	a.	.4	17.5	78.5	3.6	1.0	4.5	86.3	1.5	3.1	15,050	
		b.	-	18.2	81.8	-	1.0	4.7	89.9	1.5	2.9	15,680	
		c.	-	17.8	82.2	-	-	4.9	90.7	1.5	2.9	15,810	18.4
Fusain.	A 89582	a.	.5	10.5	71.8	17.2	1.8	3.0	74.8	.7	2.5	12,420	
		b.	-	12.8	87.2	-	2.2	3.5	90.8	.8	2.7	15,080	
		c.	-	10.4	89.6	-	-	3.8	92.6	.8	2.8	15,330	24.4
Franklin Mine, Johnstown, Cambria County, Pa. Standard sample.	A 77862	a.	1.3	17.9	73.7	7.1	1.2	4.5	82.4	1.3	3.5	14,380	
		b.	-	19.6	80.4	-	1.3	4.8	89.9	1.5	2.5	15,820	
		c.	-	19.8	81.2	-	-	4.9	91.1	1.5	2.5	15,780	19.6
Average columnar sample.	A 81474	a.	.6	17.5	75.1	6.8	1.2	4.5	83.3	1.4	2.8	14,480	
		b.	-	18.9	81.1	-	1.3	4.8	89.9	1.5	2.5	15,630	
		c.	-	19.1	80.9	-	-	4.9	91.1	1.5	2.5	15,780	18.6
Bright	A 81482	a.	.6	18.6	79.1	1.7	.4	4.8	88.5	1.4	3.2		
		b.	-	19.0	81.0	-	-	4.8	90.6	1.4	2.8		
		c.	-	18.9	81.1	-	-	4.8	91.0	1.4	2.8		19.0
Dull.	A 81484	a.	.7	17.4	75.9	6.0	.4	4.5	84.1	1.4	3.8		
		b.	-	18.7	81.3	-	.4	4.8	90.1	1.5	3.2		
		c.	-	18.5	81.7	-	-	4.8	90.6	1.5	3.2		19.87
Granular gray (attritus)	A 81483	a.	.5	17.6	75.6	6.3	.3	4.5	83.9	1.5	3.5		
		b.	-	18.9	81.1	-	.4	4.8	90.1	1.5	3.1		
		c.	-	18.2	81.8	-	-	4.8	90.5	1.6	3.1		19.30
Fusain.	A 81485	a.	.7	10.0	83.2	6.1	2.6	3.6	84.0	.5	2.6		
		b.	-	10.5	89.5	-	2.8	3.7	90.0	.5	3.0		
		c.	-	10.9	89.1	-	-	3.9	92.5	.5	3.1		23.72
Maryland shaft, St. Michael, Cambria County, Pa. Standard sample.	A 77859	a.	1.1	15.3	78.0	5.6	1.4	4.3	84.3	1.3	3.1	14,560	
		b.	-	16.4	83.6	-	1.5	4.5	90.3	1.4	2.3	15,600	
		c.	-	15.5	84.5	-	-	4.6	91.7	1.4	2.3	15,720	19.85
Average columnar sample.	A 81475	a.	.6	15.3	76.3	7.3	1.9	4.4	83.5	1.3	1.6	14,350	
		b.	-	16.6	83.4	-	2.1	4.7	90.7	1.4	1.1	15,590	
		c.	-	15.3	84.7	-	-	4.9	92.6	1.4	1.1	15,800	18.78
Bright.	A 81479	a.	.5	16.5	81.4	1.6	.3	4.6	89.5	1.3	2.7		
		b.	-	16.9	83.1	-	.3	4.7	91.4	1.3	2.3		
		c.	-	16.7	83.3	-	-	4.7	91.7	1.3	2.3		19.52
Granular gray	A 81480	a.	.5	15.4	77.8	6.3	.3	4.3	84.6	1.4	3.1		
		b.	-	16.5	83.5	-	.3	4.6	90.8	1.5	2.8		
		c.	-	15.9	84.1	-	-	4.6	91.1	1.5	2.8		19.8
Fusain.	A 81481	a.	.7	10.0	77.8	11.7	3.9	3.1	79.7	.4	1.2		
		b.	-	11.5	88.5	-	4.4	3.4	91.0	.4	.8		
		c.	-	8.8	91.2	-	-	3.4	94.0	.4	.8		27.6

a - as received.
b - moisture-ash-free basis.
c - unit coal basis (Parr's formula).

separated in Fig. 5; but it indicates that the main bulk of plants has similar composition and that in the course of progressive metamorphism the changes taking place in the coal substance must have similar reactions, leading to a relatively even elimination of volatile matter (CO_2, CH_4, H_2O, O_2 and H_2), and gradual relative increase of carbon.

Physical and Coking Properties of the Various Components.—The physical properties of the bright, dull gray, and fusain components of the Lower Kittanning coal are distinct not only as to color, luster, and hardness, as pointed out previously, but in specific gravity as well. A determination of the specific gravities of the bright (woody) bands and the dull (plant micro-debris), made with the aid of a Jolly balance, shows that in all mines without exception the duller coals have higher specific gravities than the bright (woody) varieties. (Table II.)

TABLE II.

SPECIFIC GRAVITIES OF BRIGHT AND DULL COALS.

Locality.	Bright (Woody).	Dull (Debris).
Cadogan No. 1 mine, Armstrong County, Pa.	1.26	1.3
Proctor mine No. 9, Elk County, Pa.	1.26	1.29
Victor mine No. 29, Indiana County, Pa.	1.25	1.31
Ehrenfeld mine, Cambria County	1.287	1.30
Franklin mine, Cambria County	1.285	1.31
Maryland shaft, Cambria County	1.29	1.37

It must be borne in mind, however, that the differences in the specific gravities of the bright and dull coal may be accounted for in part, if not wholly, by the fact that the dull coal invariably has a much higher content of ash (Table I).

The coking properties of the various components have been the subject of numerous investigations in Great Britain, France, and particularly in Germany. All show that the bright bands in bituminous coals have good coking properties; that the dull (durain or Mattkohle) have poor coking properties, or in some instances are devoid of them; and that fusain never forms any coke and its addition to bright coal has a deteriorative effect.[10]

[10] Katwinkel, R.: Untersuchungen über die Verkokbarkeit der Gefügebestanteile von bituminösen Streifenkohlen des Ruhrbezirks. Glückauf, vol. 64, pp. 79–83, 1928.

The coking properties of the bright and dull layers of the Lower Kittanning coal have been investigated by means of simple tests using the standard method of volatile matter determination—

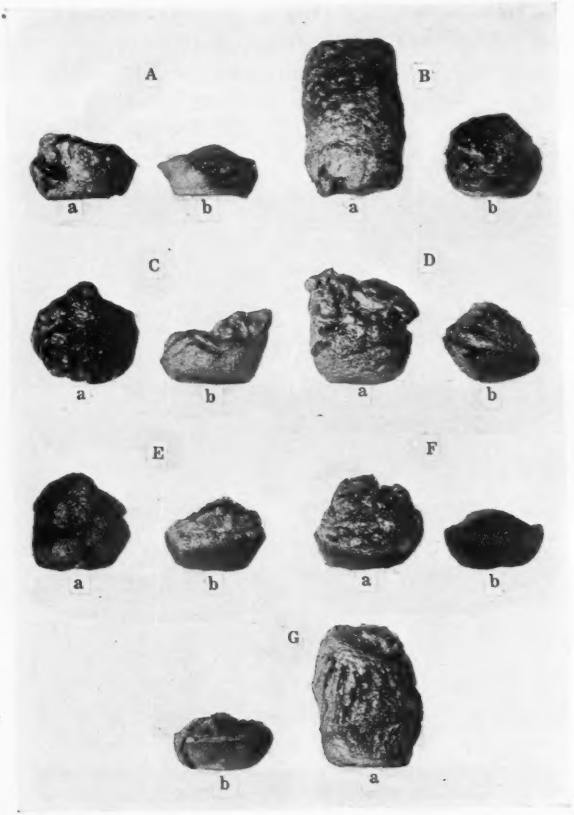


FIG. 8. Coke buttons of bright and dull coal of the Lower Kittanning coal. *A*—Cadogan mine; *B*—Proctor mine; *C*—Victor mine; *D*—Franklin mine; *E*—Ehrenfeld mine; *F*—Maryland shaft; *G*—Cresson mine. Coke buttons obtained by heating 1.0000 gram of coal at 950° C. for 7 minutes. *a*—"bright" coal; *b*—"dull" or granular coal. ×⅘.

by heating one gram of powdered coal (60 mesh) in a platinum crucible at 950° C. (± 20°) for 7 minutes. The coke buttons formed by this process (Fig. 8) show that in the case of the Lower Kittanning bed the coking properties of bright coal are higher than those of the dull or gray components of coal. The greatest contrast in the coke buttons is found in the case of the Cresson mine. Yet the only difference in the chemical analyses of these components is seen in their ash content (2.8% in the bright coal and 9.3% in the dull). In the case of the Cadogan mine the differences in the chemical composition are more noticeable, but the difference in the ash content is not as large—2.9% in the bright and 4.5% in the dull—and the coking properties differ but slightly.

This accords with conclusions that the coking properties of coal can not be predicted from its chemical analysis.

In the opinion of the author, the explanation of the coking properties must be sought in the structure and chemical composition of the various components of the coal.

Under the microscope the typical bright bands are plainly seen to have been derived from wood or bark of the trees contributing to the coal seam. The cell structure is in some instances very faint and almost obliterated; in others it is quite distinct and easily recognizable (Fig. 9, *A*).

The microstructure of the duller bands of coal exhibits considerable variety. (1) It may be almost entirely composed of fine shreds of modified wood with a small number of microspores scattered throughout the band (Fig. 9, *B*). In such cases the difference in the chemical composition between the dull and the bright bands of the same mine is slight, and the coking properties of the bands do not differ greatly (Cadogan mine). (2) It may represent a conglomerate of micro-debris consisting of accumulations in varying proportions of mega- and microspore exines, pollen grains, resins, waxes, easily recognizable or highly macerated fragments of wood, translucent or opaque groundmass (more highly carbonized substance), and fusainized plant tissues (Figs. 10, 11). The chemical composition of the spore exines,

waxes, and resins is distinct and it also differs (except in the coal substance carbonized beyond anthracite rank) from that of modified wood and colloidal degradation matter. But the chemical analyses representing the composition of the total mixture *may not always* indicate whether a band consists of large accumulations of spore exines or cuticles embedded in opaque groundmass or whether it is almost entirely composed of modified wood and its degradation products. The chemical analyses of the two

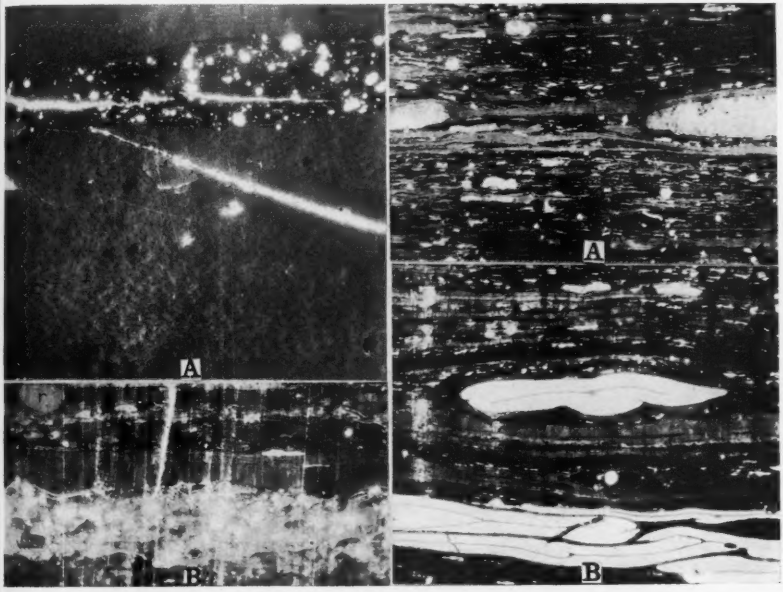


FIG. 9 (left). Vertical thin sections of Lower Kittanning coal. *A*. Microstructure of typical bright band. Note distinct "woody" cell structure in lower part; dark parting above is high in ash. × 110. *B*. Modified wood with some microspores and resins (*r*) *in situ*. × 110.

FIG. 10 (right). Vertical thin sections of dull bands from Lower Kittanning coal. *A*. Plant micro-debris, mostly woody matter, with some microspores in opaque groundmass. × 85. *B*. Macro- and microspores, and modified wood in opaque groundmass. × 85.

morphologically different bands may be identical, yet their coking properties vary greatly (Cresson mine).

The coking property of a dull band, composed of a large amount of opaque substance or fusainized plant tissues, with accumulations of plant micro-debris, resins, and waxes, is very feeble, as the greater part of its components are either non-coking—fusain, opaque ground matter—or they melt and volatilize at temperatures below 500° C.—spore exines, algae, resins, and waxes.[11]

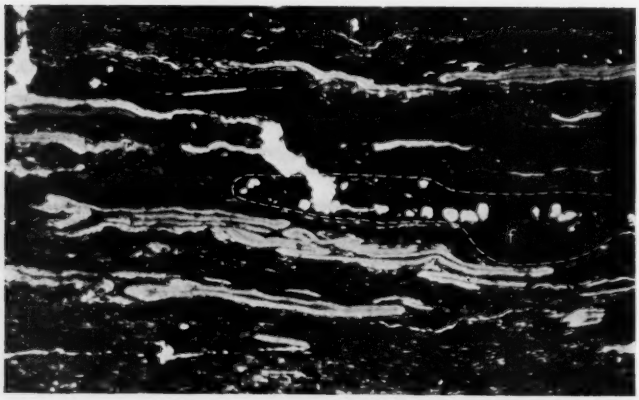


FIG. 11. Vertical thin section of a dull band in the Lower Kittanning coal. Dull band composed largely of accumulations of micro- and macrospores embedded in the opaque groundmass; f = fusain. × 80.

CAUSES OF PROGRESSIVE CARBONIZATION OF LOWER KITTANNING COAL.

A clearer and fuller conception of the progressive regional carbonization of the Lower Kittanning bed may be gained by examination of an "isocarb" map (Fig. 1). The isocarbs

[11] Stadnichenko, Taisia, and White, David: Microthermal Observations of Some Oil Shales and Other Carbonaceous Rocks. Amer. Assoc. Petrol. Geol. Bull., vol. 10, no. 9, pp. 860–876, 1926; Microthermal Studies of Some "Mother Rocks" of Petroleum from Alaska. Amer. Assoc. Petrol. Geol. Bull., vol. 13, no. 7, pp. 823–848, 1929.

of this map were made by plotting the fixed carbon percentage (pure coal basis) of all the reliable analyses at present available (several thousand analyses from about 300 localities were used).

The content of fixed carbon of a coal in some localities may differ within 2 per cent, and in some rare instances even more; nevertheless, the greatest number of coals show that in one locality the composition of the coal is similar if not identical.

The isocarbs divide the coal field into several zones with a degree of carbonization rapidly increasing in the eastward direction.

Climatic Differences.—As to the explanation that the differences in fixed carbon are due to differences in climate, as proposed by some authors, attention is called to the fact that the lines of equal carbonization have a general northeast trend (N.–N.E.). This is the direction in which climatic difference, if it existed at the time, might be looked for, since that side—*e.g.*, near Morris Run, Tioga County, through which a 75 per cent. fixed carbon line passes—is close to the northern border of the coal field and the great land mass beyond. On the contrary, however, the change is from west to east. A gain of 15 per cent. fixed carbon is found, for instance, between Salina and Bolivar, a distance of less than 20 miles. Not only is the difference in carbonization too great for any possible change of climate within this distance; it takes place within the midst of the great coal field where the climate should have been most uniform and stable (Fig. 1).

Equally difficult of explanation on a climatic basis is the rapid, almost sudden drop in fixed carbon in the area including Cresson, Glen White, and Coupon (Fig. 3, also Fig. 1), which lies close to the area of high carbonization, but in a different direction.

Differences in the Original Vegetal Composition.—With regard to the explanation of the differences in progressive carbonization as due to the differences in the original vegetal material, attention should be called to a fact which is generally recognized if not always considered. Parts of a plant may vary in composition—for example, leaves, leaf stalks, and bark are richer in carbon, but are poorer in hydrogen and nitrogen than the wood itself, and

special varieties of plants may develop special substances, like waxes, gums, or certain ethereal oils, or may accumulate special elements, aluminum, silicon, phosphorus; yet in all higher plants, in spite of individual peculiarities, the bulk of the plant body is very similar. The variation in carbon is only from 48 to 51 per cent. and in hydrogen from 5.9 to 6.5.

TABLE III.

(According to Gottlieb.)

	C	H	O	N	Ash
Pine.....	50.31	6.20	43.04	0.09	0.37
Oak.....	50.16	6.02	43.27	0.04	0.37

An illuminating study of the relationship between different botanical types of trees and the coals derived from the trees has been made by Carnot.[12] He analyzed 18 coalified tree trunks collected by Fayol at Grand Couche, Commentry, and identified by Renault. The ultimate composition of the stems *Psaronius* (fern), *Lepidodendron* (lycopod), and *Cordaites* (gymnosperm) was practically identical in hydrogen (4.80–4.88%) and nitrogen (0.39–.44%) and differed in carbon from 81.64 to 83.28 and in oxygen from 11.45 to 13.12. This shows that the differences in the original composition, even of diverse botanical varieties, are too slight to explain the great differences in the composition of the various ranks of coal.

Biologic Theory of the Ranks of Coal.—In a recent paper, Fischer[13] points out the importance of biological factors, such as bacterial and fungal action, in the formation of coal. Accepting Lieske's announcement of the finding of living bacteria in brown and bituminous coals, and the well known MacKenzie-Taylor hypothesis, based on effects of roof conditions on the

[12] Carnot, A.: Sur la Composition et les Qualités de la Houille en regard a la nature des plantes qui l'ont formée. Compt. Rend. Acad. Sci., vol. 99, pp. 253–256. Paris, 1884.

[13] Fischer, Franz: Biology and Coal. Third Intern. Conf. on Bitum. Coal, 1931, Proc., vol. 2, pp. 809–819, Carnegie Inst. Tech. Pittsburgh, Pa., 1932.

bacterial decomposition of organic matter, he suggests that they may sufficiently explain the formation of the various ranks of coal, and states that "there is no necessity for other factors."

The rôle of bacteria and biological processes in the formation of coal was recognized long ago and is described by Bertrand and Renault,[14] but the biochemical processes are terminated in the peat stage, as is shown by gradual decrease of the number and kind of bacteria with the depth of peat.

The reports of the findings of living bacteria in brown and bituminous coals by Lieske and Hoffman and in anthracite from the Primrose vein, near Pottsville, Pennsylvania, by Lippman, should be viewed with reserve. Farrell and Turner,[15] who later studied the Primrose anthracite quarried from the same place, as well as mine waters and mine dirt and dust, found no bacteria other than common living forms, which are very abundant in the mine and surface waters as well as in the soil. The unfractured coal, free from contamination, is said by these authors to contain no bacteria.

Bacterial action in the coal-forming swamps depends mainly on the level of the water and its toxicity and oxygen content.[16] The laminae, as records of climatic changes and the resultant biological action, indicate that generally similar conditions prevailed throughout the extent of the Lower Kittanning bed. The polished surfaces of all columnar samples throughout the full thickness of the bed show definitely that the morphological characteristics of the various bands are closely comparable, whether they are found in the Cadogan mine, in coal of high volatile, bituminous rank, or in the Maryland shaft, in coal of a typical low-volatile rank. In the Lower Kittanning coal, as with the coal from South Limburg, recently studied by Jongmans and

[14] Renault, B.: Recherches sur les Bactériacées Fossiles. Ann. Sci. Nat., ser 8, Bot., vol. 2, pp. 275–349, Paris, 1896; Sur Quelques Micro-organismes de Combustibles Fossiles. Bull. Soc. l'Indus. Minér., vol. 13, liv. 4 (1899) and vol. 14, liv. 1 (1900) p. 460, St. Etienne, 1900.

[15] Farrell, M. A., and Turner, Homer G.: Bacteria in Anthracite Coal. Jour. Bacteriology, vol. 23, no. 2, Feb., 1932; Fuel, vol. 11, no. 6, pp. 229–232, June, 1932.

[16] *Op. cit.*, Jour. Bact., p. 7.

Koopmans,[17] bright bands, irrespective of the rank of the coal, are always characterized by " woody " cell structure embedded in a colloidal groundmass, whereas dull bands represent aggregates of minute plant remains, in some instances of a similar character (fine shreds of modified wood) or a conglomerate of spore exines, resins, and waxes, together with fragments of wood and fusainized plant tissues.

These facts are incompatible with the explanation offered by Dr. Fischer. In addition, it must be said that the character of the roofs found in the Lower Kittanning coal is not in agreement with the Mackenzie-Taylor theory, since roofs closely similar in character cover coals of diverse ranks in some instances; in others, sandstone, shale, and slate roofs lie over coals of the same rank.

Heat as a Cause of Coal Metamorphism.—The process of coalification is divided by Erdmann [18] into two stages. His first stage, the formation of humin from cellulose and lignin, in which biological factors play a great rôle, is almost identical with White's first stage of coal formation—the biochemical. The second stage is the metamorphism of the deposit, in which higher temperatures and higher pressure cause enrichment of carbon in the organic substance and thus lead to the formation of bituminous coals. Unlike White, he believes that time plays no part, or only a subordinate one, in this stage of coal formation. On the basis of experimental work with some coals, he concludes that bituminous coals were formed at temperatures ranging between 300° and 325° C.

Gropp and Bode,[19] in a recent paper, regard high temperatures existing in the synclines of the deep coal basins as the main factor in the metamorphism of coal, the function of pressure being only

[17] Jongmans, W. J., en Koopmans, R. G.: Petrographie der Nederlandsche Kolenlagen. Jaaverslag over 1931. Geol. Bur. von het Nederlandsche Mijngebied te Heerlen, pp. 21–31, 8 pls. Heerlen, 1932.

[18] Erdmann, E.: Der genetische Zusammenhang von Braunkohle und Steinkohle auf Grund neuer Versuche. Brennstoff: Chemie, vol. 5, no. 12: pp. 177–186, June 15, 1924.

[19] Gropp, W., and Bode, Hans: Über die Metamorphose der Kohlen und das Problem der Künstlichen Inkohlung. Braunkohle, vol. 31, no. 16, pp. 277–284; no. 17, pp. 299–302; no. 18, pp. 309–313, 1932

to hinder the formation of carbonization products. The time factor is viewed as not important. In their experiments metamorphic changes were accomplished in from 6 to 48 hours.

High temperatures derived from intrusive and igneous rocks produce metamorphism in the contact coal, but the effect is only local, and the resulting products resemble natural coke more than they do a higher rank coal. The areas of known post-Cambrian igneous rocks (chiefly intrusive in the Triassic red shale) nearest to the Lower Kittanning coal are in Adams County, within 90 miles of the higher rank (low-volatile) coals. The coals of the Broad Top field (Lower Kittanning) lying some 30 to 35 miles nearer to the intrusives are, however, less carbonized than those of the Johnstown-Windber area.

No batholiths are known to be present under the Lower Kittanning coal in the areas where the coals have the higher fixed-carbon content.

The isocarb map shows that coals found in the deepest part of the bituminous basin, beneath the maximum thickness of the Permian, in southwest Pennsylvania, are less metamorphosed. If the advancing carbonization is due to increase in thickness of cover in the same direction, as has been argued by some students,[20] there should be a thickening of post-Kittanning rocks toward the Allegheny Front. On the other hand, the cited geological reports fail to show any important thickening of the Conemaugh and Monongahela formations toward the eastern border of the bituminous field, or in the Board Top field to the eastward. In short, the aggregate of the superposed strata is not now, and apparently never has been, appreciably greater at the Allegheny Front along the Windber district than in the central area of the syncline. Along the Allegheny Escarpment from the region embracing Coupon southward to the Pennsylvania-Maryland boundary, that portion of the Pottsville below and including the Sharon conglomerate and shales is stated by David White to be wanting, a barrier having extended from Maryland at least as far north as Sandy Ridge.

[20] Gropp, W., and Bode, Hans: *op. cit.*, p. 25.

The Devonian formations, on the contrary, thicken rapidly to the eastward and present much greater thicknesses at the Allegheny Escarpment than is indicated by bore holes in the syncline and farther west.

Thrust Pressure Theory.—The effects of tectonic disturbances on the characters of coal as observed in the field were definitely recognized by Hoffmann [21] as early as 1885, in his studies of the Rocky Mountain coal fields of Canada. He found that (1) the coals in the Central Belt are of "lignitic" rank, (2) those found in the innermost belt are bituminous in rank, and (3) the coal fields located in the mountains themselves are anthracites or semi-anthracites. He did not, however, offer any theory in explanation of this fact.

The theory of progressive regional carbonization, or metamorphism of coals under the influence of geodynamic forces, has been mainly developed by David White [22] and is found in several publications extending over a number of years.

As the result of the critical examination of the various theories of progressive metamorphism in the light of the facts known from field observations by many geologists, and his own extensive and thorough studies of the coal fields of the United States, White [23] reaches the conclusion that the process of organic sedimentation is completed in the peat stage of coal formation, with cessation of the biochemical processes (bacterial action), and that all subsequent chemical changes are due to geologic factors and conditions. These he calls geochemical or "dynamo-chemical." The outstanding effects of the dynamo-chemical process are marked physically by compaction, elimination of water, de-

[21] Hoffmann, G. C.: Chemical Contribution to the Geology of Canada. Coals and lignites of the North-West Territory. Geol. Survey of Canada, Ann. Rpt. 1885, pt. M, pp. 1–44. Montreal, 1885.

[22] White, David: Some Problems in the Formation of Coal. ECON. GEOL., vol. 3, pp. 292–318, 1908; The Origin of Coal. U. S. Bur. Mines Bull. 38, 1913; Some Relations in Origin between Coal and Petroleum. Wash. Acad. Sci. Jour. (map), 5, pp. 189–212, 1915; Progressive Regional Carbonization of Coals. Amer. Inst. Min. & Met. Eng. Trans., Feb., 1925.

[23] White, David: Some Problems in the Formation of Coal. ECON. GEOL., vol. 3, pp. 292–318, 1908.

velopment of joints, and cementation, and chemically by the devolatilization of the organic matter. They are characterized by the loss of oxygen and hydrogen and the relative increase of carbon. The idea that the regional metamorphism of coals is accomplished mainly as the result of thrust compression exerted differentially and intermittently through long periods, in which lapse of geologic time and also heat play rôles, as Dr. White points out, was not entirely new. It had been advanced by a number of field geologists; "yet it has in general been rejected, even by those who at first advocated it, on account of the seeming importance of certain supposedly conflicting facts, so that there are few except among American geologists who are convinced of its adequacy and validity." [24] But, according to Dr. White,

> . . . the seemingly adverse facts when rightly interpreted, are conclusively corroborative rather than combative of the theory.
>
> Buckling and overthrusting of the strata absorb the thrust, relieving the pressure and averting its greatest intensity as well as its full duration. Accordingly, the coals involved in the steep folds and for some distance behind the thrust faults are less altered than those in more competent rocks along strike subjected to approximately the same force, the differences being found to correspond in general to the extent to which the arc is shortened and the thrust compensated by the folding and thrust faulting, and apparently to the depth of the displacements.[25]

Thrust-Pressure as the Cause of the Progressive Regional Metamorphism of the Lower Kittanning Coal Bed.—The isocarb map previously mentioned (Fig. 1) shows that the region comprising southern Cambria County and the northeast corner of Somerset County and including Johnstown, St. Michael, and Windber is marked by the highest stage of carbonization of coals to be found in any part of the bituminous coalfield of western Pennsylvania. The carbonization along the Allegheny Escarpment to the south is somewhat less than in the Johnstown-Windber area, and to the north the decline in the carbonization near the Allegheny Front (vicinity of Glen White and Coupon, Blair

[24] White, David, and Thiessen, Reinhardt: The Origin of Coal. U. S. Bur. Mines Bull. 38, p. 115, 1913.

[25] White, David: Some Factors in Rock Metamorphism (Abst.). Proc. Nat. Acad. Sci., vol. 14, no. 1, pp. 5–7, Jan., 1928.

County) appears to be rapid or even abrupt. The notably high carbonization of what may for brevity be called the "Windber district," as well as the rapid decline to the north, is in accord with the thrust-pressure theory.

The geologic map of Pennsylvania [26] shows that the region of high carbonization is flanked by an eastward-protruding broad apron-buttress of the Pocono (Mississippian) formation and older (Upper Devonian) formations, lying nearly flat. This buttress of competent horizontal formations withstood the horizontal stresses transmitted across that part of the great bay of the Appalachian Valley that lies abreast of the "Windber district" and passed on, *with progressive absorption*, the compressive force towards the west, delivering its full or nearly full power against the coalfield.

On both sides of the buttress, to the northeast and to the south, the areas with less carbonized coals lie opposite areas of stronger folding and more violent thrusting, in closer proximity to the coalfield.

To the south of the buttress, folding sets in and, incidental to greater plication of the formations, the Wellersburg-Georges Creek-Potomac coal basin, embracing beds as young as Permian, was formed near the Maryland-Pennsylvania line.

To the north of the buttress, folding of an even more complex character was produced under evidently more complicated mechanical influences. Not only are the beds more strongly buckled near the margin of the coalfield, but overthrusting becomes more apparent in the same direction in which carbonization of the coals decreases along the Allegheny Escarpment. Mr. Charles Butts, who has been engaged in the study of the stratigraphy of this part of the Appalachian Valley, kindly informs the writer that within the 30 miles of present distance southeast of Tyrone the crust of the earth has been shortened not less than 5 miles by folding and faulting.[27] Obviously this foreshortening has

[26] Published by the State Topographical and Geological Survey in 1931.

[27] It is also to be observed that the mechanical conditions to the north of the area of high carbonization were such that, apparently following a relaxation of the thrust stresses, actual drop-faulting occurred at the border of the present Allegheny

compensated (neutralized) the horizontal stresses to a great extent, with indubitably great reductions in the force exerted at the Allegheny Front. The falling off of carbonization is rapid as the compensation increases.

The decrease in carbonization south of the "Windber district" is less marked, as also is the overthrusting as compared with that to the north of the buttress. It is probable that, had the Ebensburg Anticline 2 to 4 miles east of Johnstown been broken and overthrust on any considerable scale, the carbonization in this district would have been much lower.

The relation between the stages of progressive carbonization (metamorphism) of the coal on the one hand and the intensity and duration of the horizontal stresses endured by the coals under conditions of relative rock competency in western Pennsylvania is directly comparable to the relations noted in other coal fields, where overthrust faulting has afforded local and even regional escape from the full metamorphic effects of intense horizontal thrust stresses. Examples have been described and mapped by David White from the region of the Choctaw fault in Oklahoma, the Pocohontas, Pine Mountain, and other thrusts of southwest Virginia, and the Birmingham fault in Alabama. The faults last mentioned are conspicuous and give conclusive illustrations of the effects of buckling and overthrusting in compensating or neutralizing thrust pressures, the main source of the regional progressive metamorphism of coals.[28] In all these cases the coals immediately beyond the overthrust are somewhat less carbonized than at points some distance farther beyond the break or fold, just as is the case in the area of Glen White and Coupon. The occurrence of a greater decrease of carbonization immediately

Escarpment, with the result that on Tipton Run the Allegheny formation and coals (long regarded as Pocono) were dropped about 1,000 feet, so that they are now abreast of the Pocono and Upper Devonian. How far this relaxation extended parallel to the Appalachian fold trend on either side of Tipton Run is, for lack of detailed mapping, unknown. (See White, David: Age of the Coal at Tipton, Blair County, Pennsylvania. Geol. Soc. Amer. Bull., vol. 12, pp. 473–477, 1901.)

[28] White, David: Some Relations in Origin between Coal and Petroleum. Wash. Acad. Sci. Jour., vol. 5, pp. 189–212, 1915; Progressive Regional Carbonization of Coals. Amer. Inst. Min. & Met. Eng. Trans., vol. 71, pp. 253–281, 1925.

behind the fault as compared with a zone farther beyond it may be due mainly to the fact that the compensating displacement is greatest at that point and near the surface and less at depth; it may also be due in part to the transmission of a stress in the lower levels where there is compression, or even along the levels beneath the fault.

SUMMARY AND CONCLUSIONS.

The chemical and physical characteristics of the Lower Kittanning coal change in the eastward direction—*i.e.*, progressive carbonization is found to have advanced in that direction. The coal bed sampled at the Allegheny River (Cadogan mine) has 58.6% fixed carbon. At the Allegheny Front (Maryland shaft), it reaches 84.7%, unit coal basis.

The bright coal laminae are the purest components of the bed. In fixed carbon content, total carbon, hydrogen, and nitrogen, they differ but slightly from the dull coal—plant micro-débris.

Fusain in every mine examined has a considerably higher fixed-carbon content than either bright or dull coal and is characterized by a notably low nitrogen content (0.3–0.5%).

The physical characteristics of the coal bed change from mine to mine and are distinct in the various coal laminae within a single mine. The coking properties of fusain, dull coal, and bright coal differ notably.

The laminae and bands of the coal bed indicate the character and the changes in the environmental conditions at the time of deposition. They show that the Lower Kittanning coal throughout its thickness was formed from similar original ingredient plant material which, in addition to the effects of varying selective biochemical decomposition at and immediately following deposition, was subsequently subjected to various degrees of carbonization in different parts of the area.

The progressive regional metamorphism of the coal can not be adequately explained by differences in the original vegetal material or the nature and extent of the biochemical processes; nor can it be accounted for by the effect of heat due to depth of

burial, batholiths, or contact metamorphism. The thrust-pressure theory furnishes the only satisfactory explanation of the changes in carbonization of the bed in passing from the Allegheny River to the Allegheny Escarpment in western Pennsylvania.

ACKNOWLEDGMENTS.

The author gratefully acknowledges the kind and cordially interested co-operation not only of the coal companies concerned, but of the superintendents, engineers, and employees of all the mines sampled. Thanks are due also to the U. S. Bureau of Mines for analyzing the samples representing especially the different components of the bed.

The author is particularly indebted to Dr. David White for critical reading of this paper, and to the late Francis E. White for his assistance in the field.

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.

SPRING HILL GOLD DEPOSIT, NEAR HELENA, MONTANA.[1]

VERNER JONES.

INTRODUCTION.

THE Spring Hill gold mine, located four miles southwest of Helena, Lewis and Clark County, Montana, was the leading gold producer of the state during 1930, and has produced approximately 38,000 ounces of the metal.

The deposit represents a concentration of values in an intrusive rock near its contact with the Madison limestone. The ores have been classed as contact-metamorphic by Knopf[2] and Schrader,[3] and as magmatic segregations by Billingsley and Grimes.[4] After a detailed field and petrographic study, the writer concludes that the deposits were formed by endomorphic processes.

REGIONAL GEOLOGY.

The areal geology of the Helena district has been discussed in a report by W. H. Weed[5] from which the main facts regarding the regional geology are abstracted.

The geologic section consists of igneous and sedimentary rocks, the latter including Algonkian, Cambrian, Devonian, Carboniferous and Cretaceous formations. The Madison limestone of Carboniferous age is the only one of importance in this discussion. Acid and basic dikes of varying composition cut many of the

[1] Presented before the Society of Economic Geologists at the Princeton Meeting, July, 1933.

[2] Knopf, A.: Ore Deposits of the Helena Mining Region, Montana. U. S. Geol. Surv. Bull. 527, p. 101, 1913.

[3] Schrader, F. C.: Metalliferous Deposits in the Winston-Deer Lodge Area, South of Helena, Montana. U. S. Dept. of the Interior, Memo. for the Press, p. 5, Aug. 27, 1929.

[4] Billingsley, P. and Grimes, J. A.: Ore Deposits of the Boulder Batholith of Montana. Amer. Inst. Min. Eng. Trans., vol. 58, p. 642, 1918.

[5] Included in bulletin by Knopf: *Op. cit.*, pp. 86–98.

beds, and subsequent to their intrusion the entire series was folded and faulted in middle Cretaceous time.

Andesite flows followed in the Upper Cretaceous and at about the same time, or in the Eocene, the Boulder batholith was intruded. Rhyolites and dacites were extruded during the Miocene.

Metamorphism of the country rock is quite marked at its contact with the main mass of the batholith, this being particularly true where Cretaceous sediments are involved.

Some additional folding and faulting accompanied the intrusion of the "Boulder Batholith," though most of the structure is essentially as it was prior to the introduction of the magma. The Prickly Pear dome is the major structural feature in the Helena region, its center being located just north of the Scratch Gravel Hills and 15 miles north of Helena. The area involved in the present study is on the southern flank of this dome.

SPRING HILL STOCK.

General Features.—The Spring Hill stock is essentially a granodiorite mass which has intruded the Madison limestone. Its composition and structural relations indicate that it is an apophysis of the underlying "Boulder Batholith" over which only a veneer of sediments remains in the vicinity of Helena. The youngest rocks intruded by this batholith are late Cretaceous sandstones, and flows of andesites and latite. Using this evidence, Knopf [6] considers the batholith to be late Cretaceous, but Billingsley [7] prefers to call it Eocene.

The stock grades from a true granodiorite in the center to a tonalite near the borders, and locally develops a shell of pyroxenite at its contact with the Madison limestone.

Within the tonalite two gradational shells can be recognized. At some places there is no marked development of the pyroxenite, and only a few inches of an amphibole-chlorite aggregate separate the outer and more basic tonalite shell from the limestone. At

[6] *Op. cit.*, p. 9.

[7] Billingsley, P.: The Boulder Batholith of Montana. Amer. Inst. Min. Eng. Trans., vol. 51, p. 33, 1916.

other places along the border of the intrusive, the pyroxenite forms a body forty feet or more in width, grading into the outer shell of the tonalite. The workable gold ore is found associated with the sulphides in the pyroxenite and tonalite, the best values being near the limestone contact.

Numerous aschistic dikes extend out from the main stock into the limestone. They vary in width from a few inches to fifty feet. The position of the larger dikes suggests that they may have been influenced by the bedding of the limestone, although this has been somewhat obliterated by metamorphism.

The nature of the contact and petrographic relations of the intrusive to the country rock, as explained below, indicate that stoping and assimilation were important factors in the intrusion of the molten mass and the formation of the ore deposits.

On both the 200 and 300 levels of the Spring Hill Mine, blocks of limestone have been engulfed in the intrusive (Figs. 2 and 3). A mass of limestone projects into the intrusive just below the 300 level (Fig. 1). At some places there is no definite boundary between the limestone and the intrusive, as the change is of a gradational character.

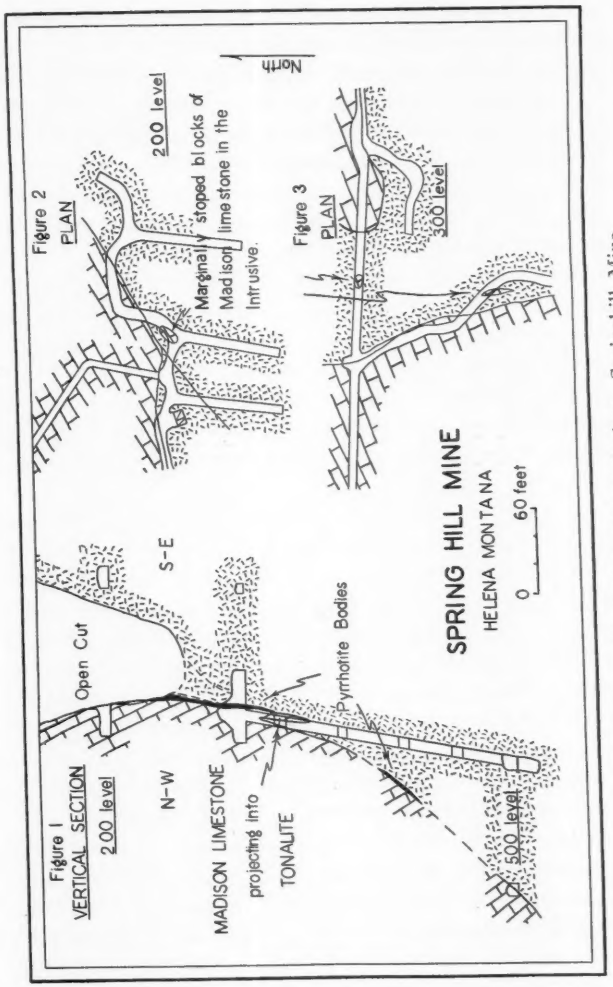
Composition of Intrusive.—As can be seen from the calculated compositions in Table I, the intrusive becomes increasingly basic

TABLE I.

CALCULATED COMPOSITIONS OF INTRUSIVE.

	1	2	3
	%	%	%
Plagioclase	63.00 ($Ab_{64}An_{36}$)	75.00 ($Ab_{63}An_{37}$)	70.00 ($Ab_{59}An_{41}$)
Quartz	16.00	11.00	8.00
Microcline	11.00	1.00	4.50
Biotite	6.00	9.00	9.00
Muscovite	0.00	1.00	0.00
Hornblende	0.00	0.00	4.00
Actinolite	0.00	0.00	3.00
Augite	0.00	1.00	0.00
Apatite	0.25	1.00	1.00
Titanite	2.00	0.50	.25
Pyrite	1.50	0.50	1.00

1. Spring Hill stock near center, granodiorite.
2. First shell of tonalite.
3. Second shell of tonalite.



FIGS. 1–3. Vertical section and plans, Springhill Mine.

from the center towards the margin, this change being indicated by the increasingly basic character of the plagioclase, the increase in dark silicates, and the decreasing quartz.

Granodiorite.—In the hand specimen this is a medium fine-grained, light gray, dense rock, commonly showing disseminated pyrite. It is less coarsely crystalline than the rocks nearer the border of the intrusive. Microscopically it is seen to be composed essentially of plagioclase ($Ab_{64}An_{36}$), quartz, microcline and biotite. Titanite and apatite are common accessories, and pyrite may be tentatively included in the latter group.

Tonalite (*first shell from center*).—Megascopically this is a medium-grained, gray rock usually showing disseminated pyrite. It is darker than the granodiorite and its granular character is more pronounced. Under the microscope the mineral composition is quite similar to that of the granodiorite except that the ferromagnesian content has increased, the microcline content decreased, and the plagioclase is slightly more basic ($Ab_{63}An_{37}$, andesine).

Tonalite (*second shell from center*).—This zone ranges from 5–15 feet in thickness. The hand specimen does not appear materially different from that of the first shell, though in places it is slightly darker in color, and of denser texture. Microscopic examination reveals a higher content of ferromagnesian minerals, particularly hornblende and actinolite. The microcline content is erratic. The accessory minerals are similar to those in the other portions of the stock. The plagioclase is composed of 59 per cent. albite and 41 per cent. anorthite.

Pyroxenite.—This forms the main portion of the ore zone although some gold extends out into the less altered tonalite. The pyroxenite is a dark gray to brownish black rock, coarser grained on the average than the tonalite. It is commonly impregnated with sulphides, pyrrhotite being most abundant, with lesser amounts of arsenopyrite and pyrite. Under the microscope the rock is seen to be composed of augite, sulphides (commonly pyrrhotite) and in many cases notable amounts of scapolite, which appears to have crystallized here instead of the feldspars. The

augite and pyrrhotite are nearly contemporaneous in their order of crystallization, though the sulphide is slightly later. Calcite, apparently of a primary nature, occurs sparingly. Figs. 4, 5, and 6 show the typical textures of granodiorite, tonalite and pyroxenite.

Granodiorite and Diorite of the Dikes.—These rocks are similar to the border-zone tonalites in texture, color and mineral composition except for quartz, which may or may not be present.

CONTACT METAMORPHISM.

Exomorphism.—New minerals and recrystallized calcite are developed in a narrow zone of varying width in the Madison limestone along its contact with the intrusive. The wider portions of this zone are due either to a gently dipping contact which brings the intrusive nearer the surface, or to the inclusion of the limestone between a dike and the stock. Field relations indicate that the latter condition exists, and has resulted in a thorough soaking of the overlying country rock by magmatic juices.

The minerals developed in the limestone by exomorphic processes are: grossularite-andradite, epidote, magnetite, spinel and diopside; these replace the coarsely crystalline limestone.

Some of the limestone near the igneous mass has been changed to a dense, hard, "red-green" rock which is a sure indication of an intrusive within a few feet. This criterion is based upon underground observations and has been used on the surface for the purpose of determining the approximate depth to the intrusive. The "red-green" rock is a replaced limestone composed of red grossularite-andradite and calcite.

Endomorphism.—This includes those changes which took place in the intrusive chiefly as a result of its reaction with the country rock. According to Grout,[8] such changes are principally due to assimilation of country rock and include "textural effects and changes due to the emanation of volatile constituents." He further states that assimilation may be either marginal or abyssal and that since the latter type occurs at great depth, only after

[8] Grout, F. F.: Petrography and Petrology, p. 225, 1932.

stoping has loosened blocks and allowed them to sink deep into the magma, the results may never be observed. Hence, the marginal type is most likely to leave its record.

The recognized conditions necessary to assimilation, as stated by Grout,[9] are: (1) Large volumes of magma with some superheat. (Daly [10] does not believe the latter necessary to the assimilation of carbonates, since water and carbon dioxide are very powerful aids.) (2) Hydrous or other mineralizer content to delay solidification. (3) Freshening of magma supply by movement. (4) Wall rock soluble in the magma concerned.

Relation of Method of Intrusion to Assimilation.—It appears that the magma intruded the Madison limestone because it was able to attack this more readily than the Quadrant quartzite on the south or the Three Forks shale on the north. It chose the most soluble and hence the most easily assimilated rock. Detailed observations underground show that the magma worked its way upward by breaking off and digesting portions of the limestone as well as by pushing it aside. Evidences of marginal stoping are illustrated in Fig. 1, which shows a projection of limestone into the intrusive, and in Figs. 2 and 3, which show small blocks of country rock free from the main mass and engulfed in the intrusive.

Bearing of the Zoned Intrusive on Assimilation Processes.—The textural and mineralogical variations of the intrusive have been pointed out above in discussing the petrography of the Spring Hill stock. The changes in the intrusive from center to border are probably due to a special set of conditions caused by the assimilation of limestone by the magma.

Daly [11] believes that carbon dioxide freed by magmatic heat and reaction is a powerful flux and that with the resulting increase in fluidity and new components the tendency to magmatic differentiation is strengthened.

Although the tendency to differentiate may have been present, the great difference in mineral composition between center and

[9] *Op. cit.*, p. 227.

[10] Daly, R. A.: Igneous Rocks and the Depths of the Earth, p. 301, 1933.

[11] *Op. cit.*, p. 518.

margin indicates that superimposed assimilation must have been the major factor in developing the shells along the borders, particularly the pyroxenite.

It seems reasonable to believe that with the introduction of the carbon dioxide from the assimilated limestone, reactions took place in the magma that resulted in a prolonged period of crystallization that ultimately resulted in the incorporation of limestone constituents in the magma. Such is thought to be the origin of the pyroxenes, amphiboles, scapolites, primary calcite and monticellite. The increasingly coarse texture of the intrusive from center to borders (Figs. 4, 5, and 6) is substantiating evidence that crystallization was prolonged near the edge of the stock.

Buddington [12] has also pointed out that the presence or absence of volatile constituents may have a marked effect on the composition of border produced.

Pyroxene aplite zones, believed to have been formed by absorption of limestone, have been noted in the vicinity of Phillipsburg, Montana, where the Madison and other limestones are intruded by granodiorite.[13] Although the composition of this zone and that of the Spring Hill pyroxenite are not exactly alike, the fundamental process of incorporating limestone constituents in the magma must have been similar.

The origin of the sulphides cannot be attributed to the reaction between magma and country rock, but these reactions kept the assimilation zone in a viscous state so that it formed a convenient means of access for late magmatic solutions. The juices penetrated along the contact and throughout the assimilation zone. Pyrrhotite and minor amounts of chalcopyrite were deposited near the limestone contact while arsenopyrite and pyrite were more widely distributed. There were also acidic emanations (pyrite-bearing quartz) which penetrated along joints and fractures zones that were formed during the process of consolidation. It is possible that ore deposition may be due to these processes.

12 Buddington, A. F.: Jour. Geol., vol. 39, pp. 258–261, 1931.

13 Emmons, W. H. and Calkins, F. C.: Geology and Ore Deposits of the Phillipsburg Quadrangle, Montana. U. S. Geol. Surv. Prof. Paper 78, pp. 120–126, 1913.

Mineralogical Evidence of Assimilation.—In view of the different compositions of the limestone and granodiorite, it is to be expected that the minerals produced will be molecular combina-

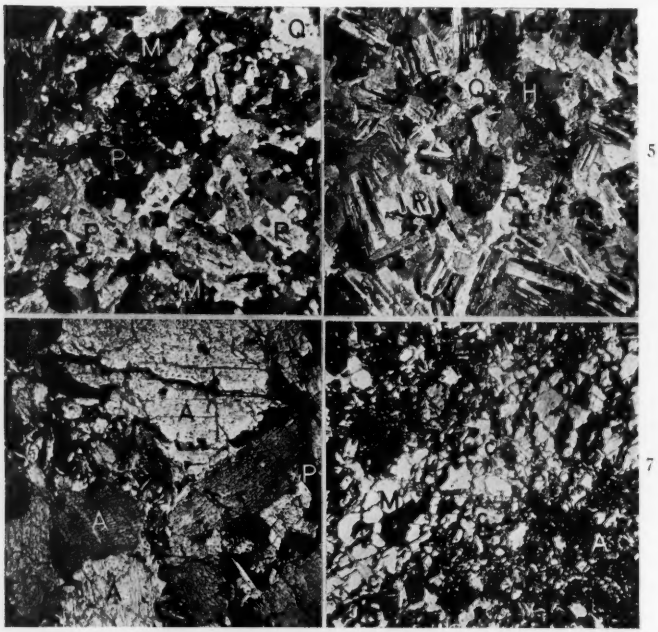


FIG. 4. Granodiorite (monzo-tonalite), center of Spring Hill stock. Plagioclase (*P*), quartz (*Q*), microcline (*M*). Crossed nicols, × 17.

FIG. 5. Outer tonalite shell of Spring Hill stock. Plagioclase (*P*), quartz (*Q*), hornblende (*H*). Crossed nicols, × 17.

FIG. 6. Typical pyroxenite. Augite (*A*), pyrrhotite (*Py*). Crossed nicols, × 17.

FIG. 7. Monticellite (*M*) altering to antigorite (*A*). Calcite (*C*). Crossed nicols, × 17.

Figures 4, 5, and 6 illustrate the textural and mineralogical changes observed in passing from center to border of the Spring Hill Stock.

Figures 6, 7 and 8 illustrate some of the characteristics of the endomorphic zone.

tions which include constituents from both sources, this being borne out by the mineralogy of the endomorphosed zone.

Among the minerals which may be regarded as definite indicators of assimilation there are found: calcite, monticellite, scapolite and zoisite. Others present and to be regarded as probable indicators include: actinolite, augite, biotite, diopside, epidote, grossularite-andradite, and tremolite.

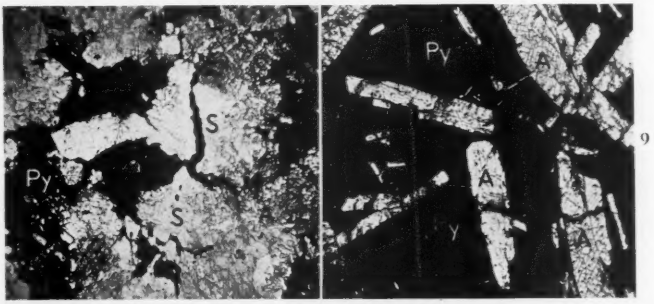


FIG. 8. Pyroxenite-scapolite rock. Augite (*A*), pyrrhotite (*Py*), scapolite (*S*). Crossed nicols, × 17.

FIG. 9. Augite (*A*), pyrrhotite (*Py*), from border of massive pyrrhotite body. Plane polarized light, × 17.

The predominance of calcium-aluminum and calcium-magnesium silicates is significant. Daly [14] has pointed out that CaO introduced into a superheated magma may inoculate the solution and result in an early separation of lime-bearing crystals so that the residual liquid is more alkaline than if not contaminated. He gives diopside as an example of this early separation, and states that it has a desilicating effect due to the fact that its foreign lime combines with 2.5 times its own weight of silica. Bowen [15] regards monticellite in a similar light.

It is of interest to note that of the fourteen criteria listed by Grout,[16] as suggesting assimilation, nine apply to the conditions

[14] *Op. cit.*, p. 518.

[15] Bowen, N. L.: Wash. Acad. Sci. Jour., vol. 13, no. 1, p. 2, 1923.

[16] *Op. cit.*, p. 230.

observed at Spring Hill. The other five are not applicable to a limestone-granodiorite contact. It appears then that the Spring Hill stock is a mass exhibiting the features of marginal assimilation and true endomorphism.

Hydrothermal Alteration.—Following the formation of the exomorphic and endomorphic silicates, there occurred considerable hydrothermal alteration of these minerals, as well as of some of the original silicates of the intrusive. These changes consisted of: carbonatization of microcline, plagioclase, garnet, epidote, scapolite and augite; chloritization of augite, scapolite, phlogopite, actinolite and plagioclase; sericitization of plagioclase and microcline. Monticellite altered to serpentine, and tremolite to talc. Laumontite and opal occur in veinlets and are apparently unrelated to the alteration of earlier minerals.

Mineralogy.—Table II summarizes the minerals present in the intrusive, and both contact-metamorphic zones.

ORE DEPOSITS.

Relation of the Ore to Endomorphic Zone.—The ore occurs exclusively in the endomorphosed zone, although minor values may be found at almost any point within the intrusive. That mined to date has come principally from the local pyroxenite shell, which represents the most highly developed phase of endomorphism. In other words, the ore zone is confined to that portion of the intrusive representing the greatest marginal assimilation. This would include portions of the tonalite. Within this zone the sulphides pyrrhotite, pyrite and arsenopyrite occur in abundance.

The ore zone mined appears to occur where a dike breaks away from the main stock and extends out into the country rock. Its significance may be that more assimilation would be possible at such a place.

The pyrrhotite is found in massive bodies along the contact and may extend into the limestone for short distances. In nearly every case it has a pyroxenic gangue.

According to metallurgical tests the gold occurs as: (*a*) me-

TABLE II.

MINERALS PRESENT.

	Intrusive.	Endomorphosed Zone.	Exomorphosed Limestone.
Actinolite	x	*	x
Apatite	*	*	–
Arsenopyrite	–	*	–
Augite	x	*	–
Biotite	*	x	–
Calcite	–	*	*
Chalcopyrite	–	*	–
Chalcedony	–	x	–
Chlorite	–	*	–
Diopside	–	?	*
Dolomite	–	–	*
Epidote	–	*	x
Gold	x	*	–
Grossularite-Andradite	–	x	*
Hedenbergite	x	–	–
Hornblende	*	x	–
Laumontite	–	x	–
Limonite	x	x	*
Magnetite	x	x	x
Microcline	*	x	–
Monticellite	–	*	–
Muscovite	x	x	–
Opal	–	x	–
Orthoclase	x	–	–
Phlogopite	–	*	–
Plagioclase	*	x	–
Pyrite	*	*	x
Pyrrhotite	x	*	x
Quartz	*	x	–
Scapolite	–	*	–
Sericite	x	x	–
Serpentine	–	*	–
Silver	–	x	–
Spinel	–	–	x
Talc	–	x	–
Titanite	*	*	–
Tremolite	–	*	–
Zoisite	–	*	–

Explanation: * = Significant amounts; x = Minor amounts; – = Absent.

chanical mixtures with the sulphides pyrite and arsenopyrite, the pyrrhotite being unimportant as an ore mineral; (*b*) in the native state, disseminated through the silicates of the intrusive.[17]

A report by James T. Norton[18] on the "Cyanidation of the Spring Hill Flotation Concentrate" includes the following state-

[17] Personal communication. L. A. Grant.

[18] Private report to Montana Mines Corporation, 1931.

ment: "So far as I have been able to determine, the gold contained in the concentrate is in the metallic form and not chemically combined with another element. The metallic gold is evidently of various sizes and has been deposited along the crystal faces of the minerals and, as the assays indicate, in a greater proportion and more closely associated with the arsenopyrite and pyrite minerals."

F. A. Linforth [19] states that "the higher grade portions of the deposit are characterized by the presence of arsenopyrite."

The writer has observed that the arsenopyrite is not always associated with high values. Along the 420 west drift there is

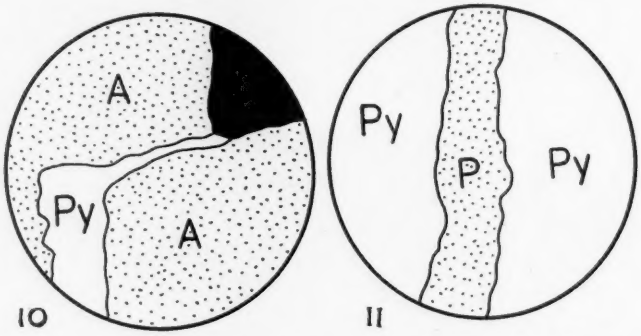


FIG. 10. Arsenopyrite (*A*), pyrrhotite (*Py*) relations. Silicates (black). × 50.

FIG. 11. Pyrrhotite (*Py*), pyrite (*P*) relations. × 25.

a great deal of arsenopyrite but assay maps show that none of the values here are greater than 0.055 ounce per ton. A carefully selected check sample ran only 0.05 ounce per ton. Unfortunately no check samples were taken at other points.

The foregoing facts lead to one of two conclusions: either the arsenopyrite is not an important ore mineral, or it carries gold only locally. Numerous tests have shown the pyrrhotite to be a poor ore mineral, if it is an ore mineral at all, and if the arseno-

[19] Personal communication.

pyrite is omitted it leaves pyrite to carry the gold. However, there are large quantities of useless rock impregnated with pyrite.

Sulphide Relations.—Microscopic and mineragraphic examination shows the sulphide relations to be as follows: (1) Arsenopyrite; (2) Pyrrhotite; (3) Pyrite. There is good evidence of an overlapping of crystallization in the case of arsenopyrite and pyrrhotite. Some of the sulphide relations are shown in Figs. 10 and 11.

The arsenopyrite occurs as veinlets filling fractures and as disseminations in the endomorphic zone (in both the pyroxenite and tonalite). The pyrrhotite occurs almost exclusively as bodies and disseminations in the pyroxenite and in the scapolite-pyroxenite at and near their contact with the limestone. Pyrite is the most widespread of the sulphides. It occurs disseminated and in veinlets in all the rocks present and is probably, though not always, an ore mineral. A series of selected assays might establish this point but it does not seem possible to draw any definite conclusions at present.

GENETIC CLASSIFICATION.

Knopf [20] places the deposit in the contact-metamorphic group because much of the gold-bearing rock contains lime-silicates. Schrader [21] regards the ores in the same light. Billingsley and Grimes [22] consider the ores to be magmatic segregations, their opinion being based on a private report to the Anaconda Copper Mining Company by F. A. Linforth. The evidence is presented in an earlier article by Billingsley [23] in which he states that he believes the pyroxenite of the Spring Hill mine to be an "original basic border."

In the Highland Mountains, Silver Bow county, on the southern edge of the batholith, Billingsley finds that

[20] *Op. cit.*, p. 101.
[21] *Op. cit.*, p. 5.
[22] *Op. cit.*, p. 642.
[23] *Op. cit.*, pp. 39–42.

the contact is marked by a profusion of basic inclusions, normally under a foot in diameter, but ranging up to 50 feet. These inclusions are in general fine-grained diorite, slightly more basic than the batholith itself. They show a slight alteration on the edges, are generally of angular form, and are distributed within the granite impartially on limestone, quartzite, and andesite contacts. These facts, together with the absence of any phenomena suggestive of magmatic segregation, lead to the conclusion that the diorite fragments represent an early basic crust of the batholith, caught up and included in a further advance of the main magmatic mass.

This does not seem compatible with a following statement that the "original basic border" remains at Spring Hill and a final classification of it as magmatic segregation.

If the basic phase (pyroxenite) at Spring Hill represents such an "original basic border," it should have a finer texture than the center of the intrusive. The textural relations already cited (Figs. 4, 5, and 6) show that the border is more coarse-grained than the center of the intrusive mass.

Under the classification here proposed it is believed that the features of the deposit which have impressed both groups of previous investigators can be accounted for. It appears that the endomorphic process has at least made possible the entrance of the gold-bearing solutions. The writer therefore suggests that the Spring Hill ore body might be regarded as a type of contact-metamorphic deposit which would fit into the following:

Classification of Contact-Metamorphic Gold Ore Deposits.

Exomorphic	
Ores deposited in limestone	*Examples*
Gold—Arsenopyrite type	Nickel Plate Mine, Hedley, B. C.
Telluride type	Dolcoath Mine, Elkhorn, Mont.
Gold—Copper type	Cable Mine, Phillipsburg, Montana.
Endomorphic	
Ores confined to assimilation zone	
Gold values only	Spring Hill Mine, Helena, Montana

ACKNOWLEDGMENTS.

The writer wishes to thank the management of the Montana Consolidated Mines Corporation of Helena, Montana, for per-

mission to publish these results, and Professor E. S. Perry, of the Montana School of Mines, for suggesting the problem. Thanks are likewise due to Professor H. Ries and Dr. Evans B. Mayo for suggestions during the laboratory study and the preparation of the manuscript.

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SOME IDEAS ON THE OCCURRENCE OF ORE IN THE WESTERN UNITED STATES.

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INTRODUCTION.

In the 2000-mile stretch of the North American Cordillera, the occurrence of ore has been particularly studied only in the nodes of minerals which have attracted industry. These nodes, as segments of the geologic terrane, make less than one per cent of the total Cordilleran area; and the intervening areas remain in obscurity.

The data collected at these nodes have been used by the miner to guide mining and prospecting; they have on the other hand been used by the geologist, possessing the normal scientific urge for a design, to construct a theory of ore occurrence, which, of necessity, requires knowledge of regional relations. Inasmuch as the geologist, rather than the miner, has done the writing, the literature has been stressed on the side of such theory, and, as would be expected, has tended to emphasize source in the broader sense; and yet the ideas relating to source in the broader sense, though now abundant, are the most remote and inferential. In contrast, those on transportation and precipitation, though few in number, are the most immediate and tangible. Accordingly, the literature, especially that of the first two decades of this

century, is restricted in the subjects where factual control is available, and expanded where such control is still lacking and difficult to establish.

The experience of the past ten years, however, has changed the interests, both of the miner and of the geologist, and today contrast of emphasis between them is obviously fading out. The miner is being drawn beyond the exigencies of immediate geology toward more removed yet vital features such as the downward terminations of his mineral deposits and the reasons for the occurrence of his mines and districts; on the other hand, the geologist who realizes the poverty of the data available is being narrowed to those hypotheses which are capable of present verification. He is, for example, inclined to give less attention to the separation of metal from a melted or solid rock than to its precipitation from a dilute solution moving through channels. He finds telling analogies between ore bodies and the termini of hot springs and fumaroles. While, then, he does not cease to consider the broader causes of ore, he tends, for the present, toward a meeting-ground with the miner himself.

This ground stands in a region less of chemistry than of physics, for the ore body is supported on a mechanical skeleton of channels, and the ore deposition is governed principally by the movement of fluids, through such channels, on their journey toward the earth's surface; in other words, most that we now know, or seem likely to know in the near future, is referable to these channels, and once we comprehend their origins, courses, expansions, and terminations, we shall have the principal data of occurrence of the ore itself.

THE ORE INLET.

The ideas referred to in the title of this paper are intimately connected with what has come to be called the "ore inlet" or "inlets" of a district. The inlet now appears to the writers as a general feature accounting for the spread of hot fluids ascending from below into the zone of easy and abundant fracture. The depth of the point of spread, and the shape of the pattern above

that point, vary with the containing structures. A particular combination of brittle rocks and fractures may, for example, produce a deep inlet with upward expansion into a system of separate veins; another combination, which prevents spreading until the fluid has come close to the surface, may, with the multitudinous cracks that occur there, result in a three-dimensional, disseminated ore body or a funnel of irregular veins or mantos. So varied, indeed, are the structures as a whole that, however clearly structures of the particular districts studied by the writers may be understood, they must be taken as examples selected because of accessibility rather than because they are representative of all. By no possibility can the patterns that seem to emerge from these examples be expected to survive unchanged in applications to districts and depths not yet explored.

In the inlet, this discussion deals with a feature which, though long inferred, has been on the whole poorly expressed and little discussed. Its few treatments, particularly that of Loughlin on Cripple Creek,[1] indicate the abundance and clarity of the information, once it is assembled. Ore has been many times followed, as the miner has known, along intersections of fissures with rock beds or with other fissures. If a number of ore shoots existed in a vein, or as mantos following the dip of a bed, they were commonly found to converge with depth; likewise, if the ore lay scattered within an irregular mass of altered rock, the walls of the mass itself were found to converge with depth. The inlet is the point toward which the ore bodies and walls are aimed; it is the actual root of the mineralization, above which it spreads upward within containing limits in the form either of a fan or of a funnel.

Although many districts are still too shallow to reveal the inlet or inlets through which their ore was supplied, and although other districts, though mined out, fail to show the convergence referred to, still the convergence and the inlet condition are sufficiently common, as shown in recent deep development, to demand an explanation. Such an explanation is sought in this paper.

[1] Loughlin, G. F.: Trans. Am. Inst. M. & M. Engrs., LXXV (1926).

The development of the ideas concerning inlets will be understood if we first think of the changes in the conditions of the miner's work and, consequently, of his interests. Until lately, he had abundant ore, found at the surface and requiring only to be followed downward. He had to define its form for purposes of mining, its minerals for purposes of metallurgy, and its metals for purposes of the market. Thus he established kinds of ore bodies, with reference, not to origin in the strict sense, but to every-day problems, including those of title litigation. And thus the miner handed to the geologist his own picture of ore bodies.

With the mines going deeper 50 to 100 feet annually, and with the bottoms of many ore bodies finally being revealed, the convergent tendency has become marked, especially in the past 10 years, and the detail has begun to collect into a scheme. Mineral bodies of diverse kinds in the miner's definition have been found to be the upward branches and tips of a system that gathers downward into a small inlet, below which the minerals change and the valuable metal either changes or ceases altogether. In this way the distinctions of mineralogy and form made at the shallower depths of earlier mining are now being recognized as vagaries of effect coinciding with particulars of local structure. The best known examples are among the deposits of small vertical range, such as the disseminated copper ore bodies, each of which seems to have been made from several inlets, and the Comstock, Goldfield, and Cripple Creek deposits. More obscurely, deep work on the veins of the Sierras shows a fan-like downward convergence of ore bodies, and, together with other examples, suggests to the writers that most of the Cordilleran ore bodies are in effect similarly grouped, whether ended at 1000 feet or going so deep that the bottom lies below the reach of mining.

REVISION OF CONCEPTS IN ACCORDANCE WITH THE INLET IDEA.

In proportion as the idea of inlet is found to take shape, the concepts based on studies of individual ore bodies undergo revision, mainly in four respects: (1) the effects of channels; (2)

the mineral- and form-zones; (3) the guides to ore; and (4) the classification of ore bodies.

The Concept of Channels.—Although other features, such as the compositions and temperatures of the metal-bearing fluids, and their chemical interactions with the wall rocks, are significant, the changes in the channels themselves through which the fluids move exercise a dominant control over the effects that they produce. This fact brings into the investigation a new set of accessible and decisive data. That the data from this quarter are essential, is seen when it is realized that loss of heat is the principal process with which precipitation can be correlated, and that such loss commonly coincides with abrupt enlargements of the channel. So long as a channel remains uniformly small, it may, like a water main, lose heat by slow conduction into the walls, and, after developing a heat-envelope, may carry the fluid through the whole range of mining depth with a change of temperature not exceeding one degree Centigrade. Such a condition favors precipitation of mineral bodies notable for extension and uniformity. On the other hand, if the channel splits, the result is the exposure of multiplied volumes of rock to heating by short conduction and to alteration by short diffusion. The loss of heat, therefore, increases not directly in proportion to the number of openings, but in a geometrical ratio to that number; it may be abruptly multiplied by many score and the precipitation may become so sudden as to amount to a dumping of the valuable mineral load within so short a vertical distance as 500 feet, with special separations of ore bonanzas. Moreover, these effects are intensified by the breaking of new rock and the exposure of new surfaces during mineralization, and by the entrance of the fluid into the zone of circulating ground water and water-jacketed rock. The enlargements of the channel, then, and the point of its entrance into the ground water zone, make critical points for ore deposition.

Such critical points are found, for instance, where the channel passes from one rock body or layer into another which is mechanically different; for example, from a limestone into a shale, or from an igneous stock into a limestone. With approach to

the contact and the broken rock there, the channel suddenly enlarges in the way suggested above. Ore bodies lie on an igneous contact, therefore, for the same reason that they lie in other positions, modified only in degree by residual heat of the intrusion. Likewise, the absence of ore from batholiths can be attributed not only to the usual scarcity of channels there, but to the absence of abrupt enlargements in such channels as exist; in other words, the batholith is mechanically unfavorable to the creation of the appropriate channels. Again, it may properly be asked how generally the contrast between ore bodies associated with volcanic vents and those associated with plutonic intrusive masses is only a mechanical effect of the channels themselves, rather than of differentiation at the source.

Perhaps the most common locus of these critical points is the junction of the strong metamorphic or crystalline basement of old rocks (schist, quartzite, and granite) with the weak shell of sedimentary and volcanic rocks. Many Cordilleran ore districts have steep dikes of diorite, monzonite, and granite in the metamorphic or crystalline rocks and show these dikes suddenly expanding into sills and chonoliths as they enter the layered rocks above; moreover, it is at that junction that many of the districts show inlets of ore bodies spreading and branching upward. This effect is especially observable if the overlying rocks have a small total thickness and if they crumple on the basement when subjected to lateral compression; but, should the pile of overlying rocks be thick and should the lower part include strong beds, the effect described may be found above the true basement, for example, at the top of a thick quartzite overlain by shale and interbedded limestone.

The Concept of Zones.—The foregoing consideration introduces the second revised concept, that of the mineral- and form-zones. The distribution of such zones, as we know, accords with the environmental changes, which may operate through their effect on the character of the channels. The zoning of largest amplitude is expected in channels of constant dimensions, in which the dominant variable is proximity to the surface. The other extreme is found in the three-dimension expansion above the

inlet of a mineral " funnel " and is illustrated at Gilman, Colorado, where a silver-chalcopyrite-pyrite funnel expands upward from the top of a massive Cambrian quartzite through beds of limestone 200 feet thick; and spreads out under a shale roof into mantos or replacement bodies of pyrite, sphalerite, and galena that radiate from the funnel through an arc of 90 degrees.

The zoning revealed by the progressive developments and studies of mining districts, although well defined in some and symmetrical in a few, is confused in many districts by the overlapping of adjacent ore clusters, each fed from a separate inlet. The zoning is found to be most significant with respect to the individual inlet and to be much less perfect with respect to the assemblage throughout the entire district. Indeed, when complete surveys for minerals such as molybdenum and fluorine shall have been made, we may in particular cases be enabled, on the basis of certain minerals alone, to identify the zonal position of a given ore in relation to its inlet.

Although the cluster of ore bodies is the unit within which zoning is most commonly displayed, there is found to be a difference between clusters within the same district. In Tintic, for example, some inlets underlie copper and others underlie lead-zinc ores; moreover, the two kinds give some hint of systematic arrangement, for the lead-zinc is farther from the main body of latest, pre-ore intrusive than is the copper. In Cordilleran districts as a whole, however, few clusters as such have been so thoroughly explored that their relations in time and place to the pre-ore intrusives have been thoroughly determined and that their general systematic positions can be demonstrated.

In the study of zoning, then, the trend is toward relating mineral bodies to the channel as it is traced from its deepest accessible portions through its physical changes to the portions closest to the original surface. What shape these ideas will take with more deep development and more thorough portrayal of structure is now unknown.

The Concept of Miner's Guides.—The next concept to be considered is that of the miner's guides to ore. As the miner is driven by the exhaustion of his ore toward discovering what

amount to new inlets and eventually new districts, he seeks larger and more momentous guides and these bring him to face larger structures. The change is illustrated by the history of Butte. Until recently, the guides there concerned ore shoots in separate veins. Now, the vein has become a local detail correlated into a larger structure; for, in a number of the deep explorations, the quartz vein of the upper levels breaks downward into a grid of small, diagonal, copper-bearing cracks that collectively make large bodies of good ore, a phase in the downward progression marking a change from the linear to the two-dimensional, horizontal pattern. This progression has become a major interest in the district and has paralleled a change from simple geometry to the higher mathematics of stress patterns, and has led to the study of granite structures by recent European method; in other words, the changed concept of ore guides in Butte already requires attention reaching far beyond the geology immediate to daily mining requirements. While attention was formerly concentrated on outlines and relations of small fault blocks, those in charge of exploration now look for ore distributed in step-like shoots inferred by the estimate of a large vein-grid pattern; and they examine this pattern for hints of still farther downward change, such as the concentration of these large structures with depth, perhaps below the limits of mining, into inlet pipes of metal-bearing breccia, the veritable roots of the district.

The history of the Tintic district is another illustration of the revision of the miner's guides. Twenty years ago, the interest was in the intersection of " good " beds by pre-ore fissures. Now, experience shows that such an intersection bears ore only where ore fluids have been led to it by channels formed on a series of special structures. These special structures involve north-south sharp " creases," or local fractured V-shaped bends in the bedding, developed to a depth of 2500 feet within the trough of the Tintic syncline; a series of three older north-west faults of large displacement; and a system throughout the district of steep northeast fissure zones younger than the folding. In these zones late pre-ore dikes and metal-bearing fluids have moved upward into inlets at the bottom of the crumpled rock. The inlets thus far

found lie only at the triple intersection of the tight creases with northwest faults and with northeast fissure zones, most of which are traversed by dikes. Nine such inlets have been found, each with its system of pipes, mantos and finger-tip terminations pointing toward the surface. In Tintic mining, then, the bed-fissure intersection has retired to the position of a feature within the cluster, and the major effort has moved on to the identification of the places where the inlets of the clusters are to be found.

In Cananea, a similar revision of guides can be seen, for the great richness of the Colorada pipe has turned exploration from scattered, shallow, low-grade, to compact, deep, high-grade ore bodies. This pipe and others somewhat similar have aroused the expectation in other districts that disseminated bodies of copper, gold, lead, and zinc may be made to yield, below the sparse superficial metallization, a more concentrated ore at deep points of entry.

Much the same kind of change of the guides has taken place in Hedley. Prior to complete development, the gold deposits there were spots and runs on beds, apparently beginning nowhere and ending nowhere. The problem was to cut through faults and pick up extensions, or when one bed was mined out, to get into an adjacent bed. Now, an including pattern is seen, consisting of mantos leading down the dip, and arranged along bedding crumples which are joined radially to a central breccia mass or central structural localizer.

The Calico district is a small, complete example of the same tendency. Large ore shoots in veins were worked at first; then, below, as in Butte, a veinlet-grid zone; below this, a breccia pipe of low grade ore, and finally an alignment of pipes along a major regional fault. These changes occur within 1000 feet of depth and accord with the change from bedded tuffs and lavas to massive flows.

Altogether the recognition of the larger, as contrasted with the smaller guides, has been quickest in the shallow and slowest in the deep districts. The exceptional progress in Butte is due to the combination of intense geological study combined with single ownership, deep development, and a structural pattern that is not

too coarse to be recognized. Districts such as the Mother Lode have a pattern that is larger, and therefore more difficult to explore and comprehend.

The Concept of Classification.—The revision of the three concepts above discussed suggests a revision of the classification of ore bodies. This is the fourth changing concept under discussion.

If classification has the purpose of emphasizing identities and contrasts in the occurrence of ore, and if occurrence is to be traced back toward fundamental cause, the idea of the inlet gives hints of a possible new grouping.

For illustration, let us view the miner's simplest classes, as follows:

Form	*Minerals and Metals*
(1) Vein.	(6) Gold-quartz-pyrite.
(2) Pipe, chimney.	(7) Zinc-lead.
(2*a*) Pipe-breccia, barren.	(8) Lead-zinc-silver.
(2*b*) Pipe-breccia, ore-bearing.	(9) Copper.
(3) Mass.	(10) Copper-silver.
(3*a*) With sulphide disseminated.	(11) Garnet-epidote-pyrite-chalcopyrite.
(3*b*) With sulphide aggregated.	(12) Garnet-epidote-pyrrhotite-arsenopyrite-gold.
(4) Manto.	(13) Quartz-sericite.
(5) Bed.	(14) Quartz-orthoclase.

These are general, descriptive distinctions; no one term or combination of terms has identical connotations in different districts, and repeated error can be avoided only by special redefinition of each term as it is used in each place. But, once inquiry is made as to why the ore is there, these distinctions become less pertinent than others that are larger; for, within the ore cluster and springing from the same inlet, the deposits pass through abrupt changes from one form and mineral group to another, which, before the emergence of the including pattern, were thought to be widely separated in origin and method of deposition. The Tintic district, for example, has from top to bottom in a single cluster the following classes of deposits based on form and mineral composition:

Lead-zinc-silver mantos having the shapes of petals and ranging far along limestone beds.
Zinc-lead mantos in limestone beds.
Ore-bearing breccia pipe with low grade zinc-lead-silver.
Barren breccia pipe in shale and limestone.
Gold-quartz-barite-pyrite-tetrahedrite veins in Algonkian quartzite.

The writers' idea of classification, then, for miners' purposes, is to employ these elements of form and mineralogy as descriptive detail, and in those districts in which the inlet picture has taken form, to make the classifying divisions: first, the shape of the cluster, whether it is funnel-like, or fan-like; and next, the position of the inlet in the district structure, whether on an old through-going governing fault or some other feature, and finally the position of the cluster with reference to the surface at the time of its formation.

Moreover, if the miner's classification tends to be modified, so also does that of the geologist who is more concerned with matters of genesis. For, *deep, middle ground,* and *shallow* assume new meaning in connection with the ideas of *under, in,* and *above* the inlet. Particularly, a persistent channel rising through strong, unbroken rock may " short circuit " the mineralization and deposit minerals at high temperature in and above the inlet, though the surface be less than 500 feet higher up. In other words, the general environmental classifications have to be supplemented by mechanical features pertaining to the channels in which the ore was made.

THE POSITION OF THE INLET IN THE ORE DISTRICT.

In those districts in which the inlet is well developed and known, it is found to lie on what may be called a *governing linear structure.* This structure is a steep fault or a combination of sharp fold and compressive fault. One of its characteristics is persistence both in time and in space. It extends, ordinarily, downward below the limit of ore, and outward beyond the ends of the district where, unoccupied by alteration and intrusions, it may

often be clearly seen to align with the major persistent regional structure. In certain regions, it has been proved to have originated in some geologic period older than that in which the ore was deposited. It preceded and localized intrusion; renewed post-intrusion movement along it broke the intrusive rock and localized ore; still later renewed movement broke the ore itself and might even involve surface gravels. It was, in other words, a "living" structure before, during and after the ore deposition.

This governing linear structure cuts the stratigraphic pile to the bottom and penetrates the basement to a source of heat. Examples include the thrusts of the Mother Lode, the Dividend Fault in Bisbee, up which both intrusive rock and ore have been introduced, and the northeast cracks of Morenci, which localize dikes in the granite basement, a spread of porphyry near the base of the sedimentary shell, dikes of similar porphyry within that spread, and sulphide veins in and along these dikes.

The general occurrence of the ore bodies along such a major structure is a characteristic feature of what may be called the "Cordilleran type" or "cross-cutting type" of ore body as contrasted with that of the Michigan copper area, for example, where the ore follows the beds themselves.

Before these governing linear structures were so much emphasized, the principal "idea" of the Cordilleran ore district was its position marginal to an igneous stock. Although no answer was available to the question why some igneous bodies have a rich sequence of mineral bodies, whereas others, of similar mineralogic and chemical composition, shape and size, have none, still the discovery of a good reason was expected. Now, the weakening of the connection of most of the carefully studied "contact metamorphic" deposits of the western United States to their adjacent stocks, seems to conflict with the conventional zoning-genetic scheme. The emphasis, in fact, has so shifted that the tendency is to seek an explanation that will account for the position and shape of the intrusive mass as well as for its fringe of ore. Both the intrusive rock and the ore, it is now supposed, had a common ancestor, but one did not of necessity come from the other. The high available energy of fluids derived from igneous

sources and their consequent ability to react with rocks afford a mechanism that can produce both vulcanism and ore, given only a crack going deep enough to afford release for such energy. Especially has this idea gained plausibility as deeper exploration has shown that some of the most productive stocks, such as those of Ely, do not enlarge in section downward but are mere lobes or chonoliths, bottoming at shallow depth, and even cut by dikes of pre-ore age. Evidently the enlargement of the igneous body downward is not essential, for identical effects are produced where that body pinches out altogether in depth. As the writers now believe, these lobes or chonoliths belong to a series of intrusives that worked their way in recurrent pulses up the same path from an unknown source toward the surface. Earlier stages were marked by the intrusion of sills into weak, layered rocks. Made more rigid by these sills, these rocks became broken by cross-cutting fractures along whch dikes or stocks ascended. In the wet, cold rock, near the surface, the intrusives became chilled and plugged the channel, and their upward progress was stopped, at least for a time. The newly formed plug, cracked by renewed movement of the governing structures along which it ascended, is a usual locus of ore inlets.

If, then, the inlets lie on governing linear structures, what peculiarity fixes them at one point rather than another along the strike of these structures? This resembles the question why hot springs appear at particular places along a fault. The answer is not in general well known, nor can it become well known until distinct systems of structure in many districts have been determined. The best information is in the Tintic district, where such a system has been demonstrated by extensive deep development and long-continued study. Here, as was shown earlier in this paper, the inlets are distributed on the basement at triple intersections between the northwest linear structures, involution-wrinkles in favorable beds, and northeast faults. In Goldfield, the governing linear structure is a flat, east-dipping fault along which there are several inlets for ore. This fault extends downward, through the 1000-foot pile of volcanics, to the basement

of shale and granite that underlies the district. The inlets lie in the actual intersection of the fault with the basement, and recent mapping shows that the inlets are located where steep northeast faults, in part combined with steep faults of some other system, cut the intersection of the flat fault with the basement.

Many additional examples are omitted for lack of space. The general rule that so far can be derived from structural conditions in all these districts is that wherever development has been complete and study thorough, a definite structural reason for the position of the inlet on a governing linear structure has been found. The inference is that such development and study in other districts that contain the inlet feature will yield similarly definite results.

THE POSITION OF THE ORE DISTRICT IN THE REGIONAL STRUCTURE.

As the governing linear structure is followed outward beyond the limits of the district itself, it enters the less known areas that intervene between centers of intenser study. As would be expected, lack of knowledge regarding these intervening areas so greatly overbalances the known facts that the position of intensely mineralized districts with respect to the large region that contains them may be at present only vaguely understood. Among the Sierran and Southwestern districts of the United States, in fact, the ideas of position have been little considered. In the Rocky Mountain and Great Basin regions, where interest in both oil and metals has resulted in the preparation of more extensive and continuous maps, the ideas have gone further and have lately indicated a substantial growth of general theory.

The Park City, Bingham, Tintic, Horn Silver, Iron Mountain, and Goodsprings districts, for example, show governing linear structures consisting of thrust-faults, and of crumples, creases, involutions, and wedge blocks produced by thrusting, that traverse the districts from north to south and prove beyond the district limits to be parts of a continuous Cordilleran thrust zone. From a compilation of detailed information on these and other districts in the two regions, the writers regard this Cordilleran thrust-zone

as a most important causal factor in ore deposition, and suggest reasons why this zone at intervals becomes ore-bearing.[2]

The thrusts referred to are associated with a zone of folding that extends southeasterly from British Columbia into Idaho and Montana, continuing southward and southwestward through Utah and southern Nevada, and thence continuing to the vicinity of Los Angeles. A branch of this zone extends southeastward from Montana along the eastern Rockies. The main zone, with its eastern branch, includes the principal ore districts of the region. Moreover, this zone, which may be termed the Rocky Mountain thrust-arc, is the most definite zone of crustal weakness and compression in the Rocky Mountain region and is a culmination of events which began far back in geologic time. Its importance is suggested by the fact that the Rocky Mountain thrust-arc broadly separates the Algonkian and Paleozoic basins to the west from the old continental shelf on the east, and that near the end of the Paleozoic it became a fulcrum marking a reversal of conditions and separating uplift and erosion to the west from heavy, continental sedimentation to the east.

The Rocky Mountain thrust-arc, however, is a zone of great linear extent, and ore districts within it occur at intervals of 50 to 200 miles. On searching for reasons for the distribution of these districts, it is found that the thrusts cut such older uplifts as the Uintah, and that the intersections definitely coincide with nodes of vulcanism and ore. Although not every intersection is marked by a district, and although there are districts that have not been placed on intersections, the more thoroughly studied districts of the Rocky Mountain thrust-arc are closely associated with such intersections. The pattern thus developed is compatible with the close relation of ore districts to the periphery of the Colorado plateau, as noted by Butler, for the ore districts on that periphery coincide with thrust-uplift intersections of the kind described.

In the Sierran and Southwestern regions a similar pattern of thrusting, vulcanism, and ore occurrence is suggested though less

[2] Billingsley, Paul, and Locke, Augustus: Tectonic Position of Ore Districts in the Rocky Mountain Region, A. I. M. E. Tech. Paper 501, 1933.

well established. There is a growing recognition there, as well as in the Rocky Mountain region, of a progressive historical unity, with the ore as the final outcome of a series of tectonic events.

FIELD METHOD.

The field method has recently been undergoing change in accordance with the general desire for more thorough information. The resulting newer procedure has proved fruitful in the study of the features discussed in this paper and, as applied by the writers in their work, has been in some degree shaped by the requirements of these features.

Just what the change is, becomes clear if we first consider the field method of the past. This has been essentially areal reconnaissance, and detailed study of "immediate" geology. There are several reasons for this; the public surveys, with a new country before them, have been concerned with pioneering. However much the geologists might wish to concentrate, they could not, with half the territory lacking topographic maps, gain public support for so doing. As would be expected, the surface maps, on small scales, even in the great mining districts, present generalized descriptive syntheses, incapable of verification without further data. As a tool for the collection of precise knowledge, the surface mapping of the western United States may be said scarcely to have begun. In portions of five districts only and by private enterprise, large scale maps, showing surface geology in adequate detail, have been constructed. Even the commercial urge, which was responsible for these few precise maps, has remained feeble until recently because it was thought that the mines had no geological problems whatever except those of local detail. The mapping, accordingly, has been mainly confined to underground workings, and has nowhere, except in Butte and a few other places, been other than a compilation of detail.

With the decline of production in many districts, and with the increasing demand for data to be used in the development of theory, there is a recognition of the need for a large extension of the time and effort applied to field study. Experience in deep

development now shows beyond argument that the ideas of occurrence evolved early in the study of a district are either distinctly wrong or too vague to be used as practical guides; that after six months or more of additional study they are still imperfect; and that thenceforward it is a struggle toward a perfection that is never attained, the truthful picture or model of the occurrence.

In short, mining geology requires a new kind of field study that amounts to *field experiment*. By field experiment is meant a study in the thin shell of ground that is accessible, followed by experimental projection and verification. The observations are "complete" in the sense that the scales used in mapping are successively enlarged until further enlargement is found to yield no further pertinent information. In this experiment, the surface map takes a position of increased importance; for it is found to give a framework of the ground into which the fragmentary glimpses yielded by mine workings can be properly fitted. If the opportunity to make this map is neglected, or if it cannot be made because of a thick mantle covering the bed rock, only extraordinarily numerous and costly mine workings can supply the needed information. The surface indeed becomes a theater for meticulous study. It is not a place to be glanced over hastily, but one worthy of development by trenches, pits and short drill holes, and of continuous observation with the aid of permanent monuments set close together. The breadth and substantial verity of the vista opened by accurate surface measurement should be strongly emphasized.

The study of this kind, applied by certain geologists in North America to several separated plots of one to ten square miles each, and verified by mining or other means, has been established during the past decade as capable of results which approach in definiteness those obtained in the controlled laboratory experiment.

SOME PSEUDO-EUTECTIC ORE TEXTURES.[1]

ALFRED L. ANDERSON.[2]

INTRODUCTION.

PECULIAR intergrowths of sulphide minerals which closely resemble the eutectic texture in metals never fail to arouse the interest of students of ore deposits. Many intergrowths simulating the eutectic have been described, but opinions differ as to the interpretation of these textures and much discussion has followed. Some have argued that the intergrowths result from contemporaneous deposition; others, from replacement.

It is not the purpose of this paper to review the controversy existing as to the interpretation of these textures, but to present additional examples of peculiar sulphide intergrowths and to show that those resembling the eutectic have been accompanied by replacement phenomena and are themselves the result of replacement. For those replacements that resemble the true eutectic (simultaneous crystallization) the term pseudo-eutectic will be used. These intergrowths were observed in ores from a number of veins in the Boise Basin region, Boise County, southwestern Idaho,[3] a short distance northeast of the State Capitol.

Most of the pseudo-eutectic textures are exceptionally well formed, perhaps more perfectly formed than is usually the case in intergrowths of this kind, and examples include combinations never before described. The intergrowths are between (1) galena and cosalite, (2) cosalite and brongniardite, (3) tetrahedrite and galena, (4) galena and pyrargyrite, (5) owyheeite and pyrar-

[1] Published by permission of the Director, U. S. Geological Survey, and the Director, Idaho Bureau of Mines and Geology.

[2] The writer wishes to acknowledge his gratitude to Mr. Alfred C. Rasor, teaching fellow in the Department of Geology, University of Idaho, for his assistance in the microscopic determination of the complex bismuth and silver minerals.

[3] This paper is an outgrowth of a detailed study of the geology and mineralization of the Boise Basin, Idaho, for the U. S. Geol. Survey and the Idaho Bureau of Mines and Geology.

gyrite, and (6) galena and calcite. The intergrowth between cosalite and brongniardite, however, is not a pseudo-eutectic like the others, but a eutectoid due to exsolution.

GALENA-COSALITE.

The graphic intergrowth of galena and cosalite ($2PbS.Bi_2S_3$) [4] in ore from the Mayflower vein near Quartzburg in the northwest part of Boise Basin is one of the most interesting in the group. The ore is mainly pyritic and valued chiefly for its gold, but there is a subordinate amount of arsenopyrite, sphalerite, galena, tetrahedrite, chalcopyrite, brongniardite, and the bismuth minerals alaskaite, cosalite, and perhaps others. The graphic intergrowth of galena and cosalite is illustrated in Fig. 1, and shows a striking similarity to the eutectic pattern in metals or alloys. Etching was necessary to reveal the complex intergrowth, as the two

[4] The determination of the lead bismuth mineral as cosalite is based on microchemical tests following Short (Short, M. N.; Microscopic determination of the ore minerals. U. S. Geol. Surv. Bull. 825, 1931, p. 81). The mineral reacts to all the tests for cosalite and is distinguished from galenobismutite ($PbS.Bi_2S_3$) by slowly staining differentially gray to black by HCl, whereas galenobismutite is negative to HCl.

FIG. 1. Pseudo-eutectic texture of galena and cosalite, Mayflower mine. The cosalite is distinguished by its grating structure. The clear, unetched laths are alaskaite, younger than both galena and cosalite. Difference in shading in the specimen is due to an uneven etch. × 90.

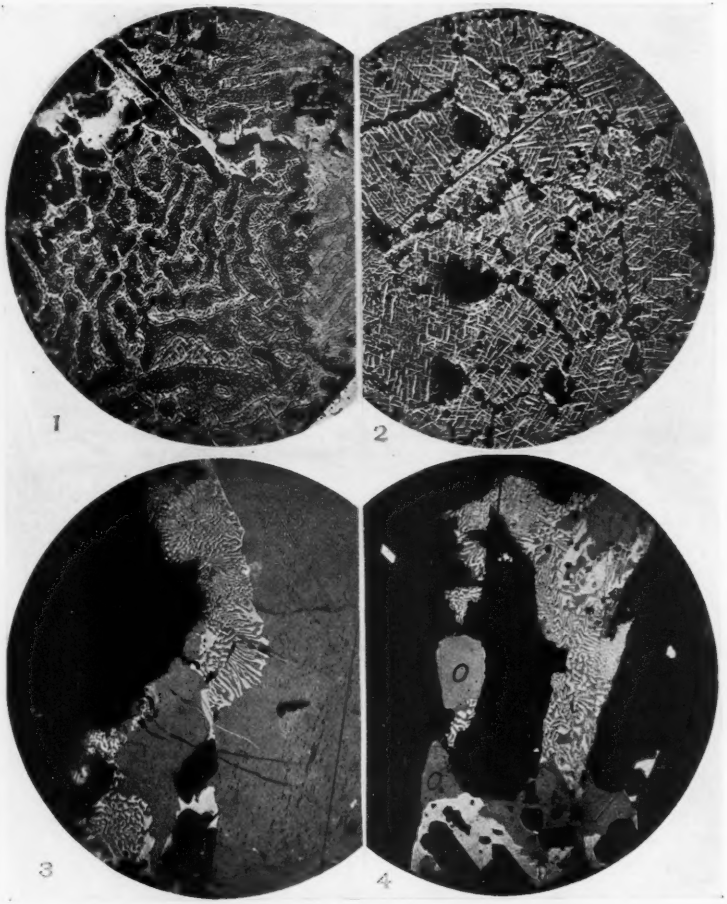
FIG. 2. Grating pattern in the cosalite produced by oriented laths of brongniardite, believed to be a product of unmixing. Network enclosing the cosalite grains consists of centrifugally replaced remnant galena, and affords an illustration of mesh structure produced by centrifugal replacement. × 90.

FIG. 3. Pseudo-eutectic texture representing replacement of tetrahedrite (gray) by galena (white). The remarkable intergrowth is in an irregular galena veinlet that cuts tetrahedrite. Black areas are holes formerly occupied by calcite, removed by etching. Washington mine. × 145.

FIG. 4. Pseudo-eutectic texture of galena (white) and pyrargyrite (gray). Mineral O is owyheeite, the black is vein quartz. Banner mine. × 145.

minerals are practically indistinguishable otherwise. At the same time the etching produces a lattice or grating texture in the cosalite.

Although the galena and cosalite (Fig. 1) have the more or less curved and hooklike forms peculiar to eutectic textures, close inspection will show that the cosalite forms a system of ramifying



FIGS. 1–4.

veinlets in the galena. The veinlets present in part a series of somewhat irregular and almost angular convex curves against the galena in the manner which Lindgren [5] considers as one of the best criteria of replacement. The cosalite veinlets are irregular in thickness, their walls are ragged, and the boundaries are serrate under high magnification. Tongues of cosalite project into the galena, much of the cosalite is convex to the galena as though the galena were being "bitten into." In some places more or less rounded "islands" of galena occur in the cosalite. In other parts of the section the veinlets are more widely separated and show that there is no volume relation expressed by the intergrowths. Any one of these relations alone might not be sufficient to prove replacement, but when considered collectively they can afford no other interpretation. These are all criteria that have been offered as evidence of replacement.[6]

The vein system is peculiarly aligned and in part sharply angular, as though controlled or influenced by galena cleavage, but absence of visible cleavage leaves the relation unproven. Apparently the replacement has progressed more or less equally in all directions through the host and with the same crystallographic orientation, as may be seen by comparing the parallelism of the grating texture in all the cosalite veinlets. There is no evidence of volume change as a result of the replacement. The bismuth mineralization is known to be primary [7] and the pseudo-eutectic intergrowth is therefore a product of hypogene replacement.

COSALITE-BRONGNIARDITE.

The cosalite in the Mayflower ore always reveals on etching a triangular lattice or grating texture (Fig. 2). This is caused by a crystallographic intergrowth in which the crystal structure of the cosalite controls the distribution of the other mineral. Most of the intergrown plates or blades are very small, but in

[5] Lindgren, Waldemar: Pseudo-eutectic Textures. ECON. GEOL., vol. 25, p. 8, 1930.

[6] Bastin, E. S., and others: Criteria of Age Relations of Minerals. ECON. GEOL., vol. 26, pp. 599–606, 1931.

[7] Ross, C. P.: Lode Deposits in the Boise Basin, Idaho. ECON. GEOL., vol. 28, pp. 339–341, 1933.

some parts of the section they are large enough to furnish material for microchemical analysis. Tests were obtained for lead, antimony, and sulphur, following Short,[8] but the test for silver was not wholly satisfactory, although fire assays of the intergrown minerals show a rather high silver content. This analysis, together with etch tests, indicates that the lathlike mineral is brongniardite ($Ag_2S.PbS.Sb_2S_3$).

The grating or lattice texture is the commonest type of a crystallographic intergrowth among minerals, but it has never been described between cosalite and brongniardite. This texture is generally ascribed to unmixing, an explanation that fits this case. The brongniardite blades or plates of Fig. 2 have sharp, smooth boundaries, and contract in width at intersections instead of showing enlargements, as would be expected from replacements. The included mineral shows no relation to mineral boundaries or fractures that commonly serve to guide replacing solutions, and at the same time it tends to be evenly distributed. The orientation differs for each grain of the enclosing cosalite depending upon the crystal orientation with respect to the plane of the section. No brongniardite was found except in the intergrowths, and this, as well as all the other relations, point only toward unmixing of a solid solution. These observations are wholly in accord with the tentative criteria[9] that serve for the recognition of the grating type of exsolution texture and distinguishing it from textures resulting from replacement.

There is another interesting feature to be observed in Fig. 2, *i.e.* the more or less perfect mesh structure produced by a third mineral bordering and partly inclosing each of the cosalite grains. This border is made up of more or less loosely united galena grains, most of them rounded or irregularly embayed, others with jagged or ragged boundaries, suggestive of residual bodies in a mass of replacing cosalite. There are less prominent grains of galena within the cosalite; these are also rounded or jagged in a

[8] Short, M. N.: *Op. cit.*, p. 183.

[9] Bastin, E. S., and others: *Op. cit.*, pp. 568–70.

Schwartz, G. M.: Textures due to Unmixing of Solid Solutions. ECON. GEOL., vol. 26, pp. 761–762, 1931.

manner suggesting residuals of replacement. It has already been explained that the cosalite is a replacement of the galena and its peculiar rim pattern in this example must be a product of "centrifugal" replacement (where replacement begins in the central part of the host mineral and works outward, leaving only a shell of the original substance). This is the only example the writer has ever seen where mesh structure has been produced by centrifugal replacement.

TETRAHEDRITE-GALENA.

Graphic intergrowths of tetrahedrite and galena are among the interesting microscopic textures in the ore from the silver vein at the Washington mine, about seven miles northeast of Idaho City, in the eastern part of Boise Basin. Similar, but less perfect, intergrowths between the two minerals also occur in ore from the Banner mine, not far east of Boise Basin. Mineralization at the two places is similar and is mainly in complex silver sulphantimonides. In the Banner vein the chief ore minerals are pyrargyrite, owyheeite, miargyrite, and proustite, associated with subordinate galena, tetrahedrite, chalcopyrite, sphalerite, pyrite, and arsenopyrite. The Washington ore contains a greater proportion of arsenopyrite and probably less pyrargyrite and proustite, but has an additional silver mineral, probably brongniardite. In both places the metallic minerals are associated with a gangue consisting largely of quartz, but locally with a little calcite that is younger than the sulphides.

The resemblance of some of the tetrahedrite-galena intergrowths to the eutectic pattern in alloys is particularly striking in the Washington ore (Fig. 3). The curved, clublike, and hooklike forms, curiously interpenetrated, are perfect imitations of the eutectic textures in metals, and if it were not for replacement phenomena in the same, and in other sections, the interpretation as a product of contemporaneous deposition might go unquestioned. But as the intergrowth in Fig. 3 is itself a part of a galena veinlet that cuts and irregularly replaces the tetrahedrite, it must be in some way related to the replacement phenomena,

for there is no evidence of more than one generation of galena.

Much of the galena forms irregular veinlets that project into or pass entirely through the tetrahedrite. The walls are uneven and do not match as would be expected in fracture fillings. The boundaries are generally ragged and convex toward the tetrahedrite. These veinlets also contain "islands" of tetrahedrite, some rounded, some very ragged, and appear as detached masses from the adjacent "mainland." Some of the islands of tetrahedrite also have more or less hooklike forms as well as rounded and irregular outlines, and these show all transitions into the intergrowth pictured in Fig. 3 as well as into widely scattered inclusions. There is everywhere great variability in the ratio of guest to host. All these relations favor replacement as opposed to contemporaneous deposition, and the replacement phenomena do not stop at the margin of the intergrowths, but extend within as shown by irregular contacts, projecting tongues, and rounded and irregular islands. It is evident, therefore, that the peculiar intergrowths are the result of replacement phenomena and have not been formed as the result of contemporaneous deposition, for the replacement proves the galena to be younger than the tetrahedrite and not contemporaneous in age.

There are similar transitions from the less perfect pseudo-eutectic textures in the Banner ore to irregular residual remnants of tetrahedrite in the host. The penetrating galena bodies are commonly rather widely spaced in the Banner ore, and detached parts of them may appear in the plane of the section as rounded or elliptical grains in the tetrahedrite (Fig. 7).

A replacement process has been ascribed by Lindgren[10] to graphic intergrowths of tennantite and galena. Consequently, a similar intergrowth produced by the same process between tetrahedrite and galena is not surprising. These replacement intergrowths are apparently unrelated to crystallographic directions of the minerals, but like the normal veinlets advance more or less evenly through the host, unaccompanied by volume changes. The

[10] *Op. cit.*, pp. 10, 12.

galena is a primary mineral and its deposition has been followed by that of the complex silver sulpho-salts, and lastly by the vein calcite.

GALENA-PYRARGYRITE.

Probably the most striking of the graphic intergrowths is between galena and pyrargyrite in the Banner ore (Fig. 4). It resembles that of Fig. 3. Not all the intergrowths are as perfect as that represented by Fig. 4, and the texture illustrated in Fig. 5 is much more common. In the latter, the galena occurs as scattered small elliptical and rounded, and more or less hook-like, bodies in the pyrargyrite, and strongly suggests replacement remnants. Replacement phenomena between galena and pyrargyrite may be observed throughout the ore and resemble that of Fig. 3. In every case the pyrargyrite has advanced irregularly into the galena along convex fronts, or has sent tongue-like projections into the galena or, most commonly, has advanced into the center of the galena grains and replaced them centrifugally. Galena islands, rounded or ragged, are common. The graphic intergrowths are clearly accompanied by replacement phenomena, and there are all transitions between unmistakable replacement structures and the eutectic-like textures. Only one generation of pyrargyrite is present; the pyrargyrite is distinctly

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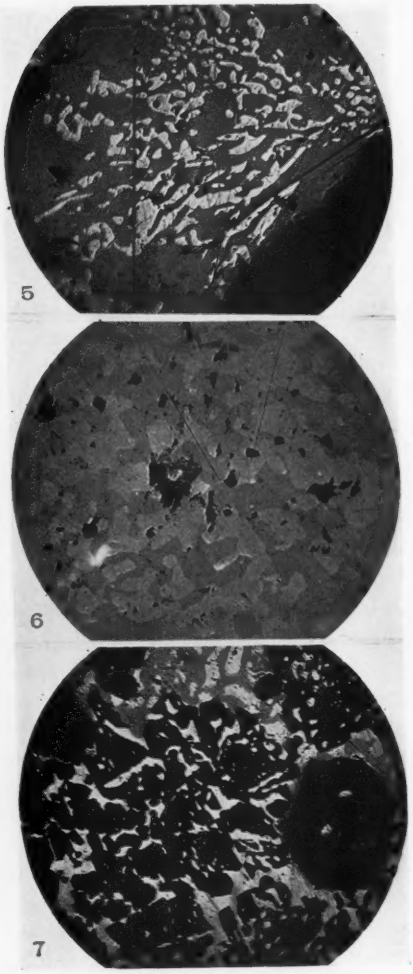
FIG. 5. Imperfect pseudo-eutectic texture of galena (white) and pyrargyrite (gray), from Banner vein. This represents an advanced stage of replacement, and much of the galena occurs as small residual bodies. × 84.

FIG. 6. Pseudo-eutectic texture of owyheeite, $2Ag_2S.8PbS.5Sb_2S_3$ (light gray) and pyrargyrite (dark gray) in the Banner ore. × 135.

FIG. 7. Pseudo-eutectic textures of tetrahedrite (gray) and galena (white), and of galena and calcite (dark gray), in the Banner ore. There is a remnant of an early intergrowth of tetrahedrite and galena in which the galena appears in the plane of the section as rounded inclusions in the host mineral. The early pseudo-eutectic has been penetrated by the younger calcite, and a second intergrowth of sulphides and calcite has been produced. The resulting pattern has been dominated by the pronounced rhombohedral cleavage of the replacing calcite. A large quartz crystal appears at right of section. × 84.



FIGS. 5–7.

younger than the galena and replaces it. It does not seem logical, therefore, to explain the intergrowths by contemporaneous deposition, especially as unmistakable associated replacement may extend to the intergrowths from all sides.

There is no record of earlier descriptions of galena-pyrargyrite intergrowths, so far as the writer is aware, but Guild [11] has shown an intergrowth of galena and proustite which resembles the graphic, but which he explains by unmixing. Inasmuch as the galena-pyrargyrite intergrowths are independent of structural lines, have no definite volume relations, and are clearly associated with replacement phenomena, exsolution can not hold; the texture must be explained by replacement. The pseudo-eutectic texture gives no hint of volume changes as a result of the replacement. In these intergrowths all the pyrargyrite has the same crystallographic orientation, and the pattern is therefore always between single individuals. If the pyrargyrite is granular, there is no pseudo-eutectic texture. This replacement is hypogene in character and was produced during the primary mineralization which ended with the deposition of calcite.

OWYHEEITE-PYRARGYRITE.

Pseudo-eutectic intergrowths of owyheeite and pyrargyrite also occur in the Banner ore, but in general the texture is not as common nor as perfect as in the other mineral combinations. In the intergrowth illustrated in Fig. 6, part of the owyheeite has curved and hooklike forms, and there are also isolated spherical and elliptical grains. Again, there is abundant evidence of associated replacement between the owyheeite and pyrargyrite (using the same criteria as before), and in most of the ore the pyrargyrite has advanced into the owyheeite along convex fronts or has penetrated in irregular veinlets unrelated to crystal structure and grain contacts. There are also rounded and irregular islands of owyheeite in the pyrargyrite. Evident replacement structures show all stages of transition to the pseudo-eutectic and suggest proof

[11] Guild, F. N.: The Enrichment of Silver Ores. The Laboratory Investigation of Ores, Chap. XI. McGraw-Hill, 1928.

of the replacement origin of the intergrowths. As before, the replacement is independent of structural lines in the host, such as characterize exsolution textures. There is also evidence that the replacing mineral has the orientation of a single individual, which leads to the suggestion that graphic intergrowths only develop between single grains or crystals, and are not characteristic of granular aggregates.

GALENA-CALCITE.

Graphic intergrowths of galena and calcite are rather common in the ores of the Boise Basin and the surrounding region. The most striking intergrowth is in ore from the Banner mine (Fig. 7). As in all veins throughout the region, the calcite is late and fills fractures in the sulphides or forms drusy crusts on the ore. The illustration is particularly interesting because it also contains an earlier pseudo-eutectic tetrahedrite-galena intergrowth into which the calcite has penetrated. This calcite intergrowth lies in the wall of a calcite vein which fills a fracture in the ore and passes through the galena and other minerals. The galena, therefore, is not younger than the calcite and does not penetrate the calcite, as the illustration at first glance might suggest.

The galena and, to lesser extent, the tetrahedrite form sharp, hooklike bodies, in part as detached veinlets with prominent jagged offshoots. They also occur as small rounded and elliptical bodies in the calcite in the manner suggestive of replacement residuals. The alignment of the sulphide bodies is especially interesting and at first perplexing because of the suggestion that they may be following the calcite cleavage, and therefore are a replacement of the calcite. There can be no doubt but that the rhombohedral cleavage of the calcite is responsible for the marked angularity and the alignment of the sulphide bodies to produce a rather distinct rectilinear pattern. The pattern in this case has evolved as such because of the tendency of the calcite to replace the sulphides idiomorphically, or to impress its pronounced cleavage on the invaded minerals. The sharp, straight contacts between part of the calcite and sulphides suggest such idiomorphic impression,

and the fact that the sulphides do not send tongues into the calcite, or swell into the calcite, but instead appear as small rounded grains in the calcite or as having been " bitten " into, afford additional evidence of the replacing action on the sulphides.

Intergrowths of galena and calcite observed in other ores in the region are usually less perfect. In every case, the calcite shows unmistakable signs of replacing the galena. It is not common to find carbonates replacing sulphides in ores, and it is not a prominent process in this region, but where it has occurred, peculiar textures simulating the eutectic have been produced.

OTHER INTERGROWTHS.

Poorly-formed pseudo-eutectic textures were observed in the Banner ores between galena and owyheeite and between tetrahedrite and pyrargyrite. Some of the patterns are similar to those between galena and pyrargyrite (Fig. 5), but most of the intergrowths are even less perfect and consist of more widely scattered grains of the host mineral, or, as in Fig. 7, between tetrahedrite and galena, of widely spaced grains in the host.

CONCLUSIONS.

In every combination here described, except of cosalite and brongniardite, the graphic texture has been associated with replacement phenomena and actually represents a replacement of one mineral by another, and the one exception must be construed as produced by unmixing. These replacements, and therefore the textures, have been mainly independent of structural lines in the host, and the only one in which cleavage has certainly played a rôle in influencing the pattern is in the case of calcite where the cleavage of the replacing mineral has dominated the resultant intergrowth. It also appears that the invading mineral has the same orientation over large areas, and this may be of greatest importance in producing the eutectic type of texture. The replacements are without volume change, and may be wholly physical as between galena and calcite, or partly a chemical substitution

with partial removal and substitution of certain elements. All these pseudo-eutectic intergrowths are the result of hypogene replacements. The nature and behavior of this process fits well into the general hypothesis of pseudo-eutectic textures advanced by Lindgren.[12]

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[12] *Op. cit.*, pp. 10–12.

PETROGRAPHY AND ORIGIN OF THE FULLER'S EARTH OF SOUTHEASTERN MISSOURI.[1]

VICTOR T. ALLEN.

Definition of Fuller's Earth.—Fuller's earth is a clay that has marked ability to remove color from mineral, vegetable or animal oils. Originally, fuller's earth was used for fulling or removing grease from cloth, but now it is used chiefly for bleaching and clarifying mineral and organic oils.

Mineral Composition of Fuller's Earth.—All the important commercial fuller's earths have been shown to be composed mainly of the clay mineral montmorillonite $(Mg, Ca)O.Al_2O_3.5SiO_2(5–8)H_2O$. Some Texas fuller's earth may be an exception, but as yet its exact mineral composition is uncertain.[2] Kerr [3] has demonstrated that smectite, regarded by some as the constituent of fuller's earth, has the identical optical, chemical, and x-ray properties of montmorillonite, and that montmorillonite is the more satisfactory name for the clay mineral of fuller's earth.

Extensive deposits of montmorillonite occur in southeastern Missouri, especially in Stoddard and Scott counties, that are promising potential fuller's earths. Samples from several localities were collected by the writer and W. Farrar, Geologist, Missouri Geological Survey. These belong to the Porters Creek formation of Eocene age and are of the same stratigraphic horizon as the deposits now being commercially worked at Olmstead, Illinois. A comparison of the mineral composition of the Missouri deposits with that of the fuller's earth produced in Illinois, Georgia, Texas, and England follows.

[1] Published with the permission of the Director, Missouri Geological Survey.

[2] Broughton, M. N.: Texas Fuller's Earth. Jour. Sed. Pet., vol. 2, pp. 135–140, 1932.

[3] Kerr, Paul F.: Montmorillonite or Smectite as Constituents of Fuller's Earth and Bentonite. Amer. Min., vol. 17, pp. 192–198, 1932.

TABLE I.

OPTICAL PROPERTIES OF MONTMORILLONITE FROM MISSOURI, ILLINOIS, AND OTHER LOCALITIES.[1]

Locality.	Refractive Indices.		Birefringence, $y - \alpha$.	Optic Angle 2 V.
	α.	$y \pm .003$.		
* Olmstead, Ill.				
Top, Standard Pit	1.500	1.523	.023	13° ±
Middle, Standard Pit	1.499	1.522	.023	small
Bottom, Standard Pit	1.500	1.523	.023	small
Top, Sinclair Pit	1.500	1.523	.023	small
Middle, Sinclair Pit	1.499	1.522	.023	13° ±
Bottom, Sinclair Pit	1.500	1.523	.023	12° ±
* English Fuller's Earth, Bath	1.481	1.502	.021	small
* Georgia Fuller's Earth, Twiggs Co.	1.495	1.517	.022	10° ±
* Texas Fuller's Earth, Bexar Co.	1.492	1.514	.022	small
Missouri				
Ardeola 12 ft. above Cretaceous	1.480	1.501	.021	small†
19 ft. " "	1.480	1.501	.021	small
33 ft. " "	1.503	1.524	.021	small
44 ft. " "	1.503	1.524	.021	small
Avert 5 ft. " concretions	1.500	1.521	.021	small
10 ft. " "	1.503	1.524	.021	small
15 ft. " "	1.503	1.524	.021	small
23 ft. " "	1.503	1.524	.021	small
28 ft. " "	1.500	1.521	.021	small
30 ft. " "	1.503	1.524	.021	small
Zeta 25 ft. " road	1.503	1.524	.021	small
30 ft. " "	1.503	1.524	.021	small
39 ft. " "	1.503	1.524	.021	small
44 ft. " "	1.503	1.524	.021	small
Oran Bottom	1.490	1.511	.021	small
Middle	1.490	1.511	.021	small
Top	1.495	1.516	.021	small
S.17, T.27 N., R.11E. Wm. Emery Farm	1.503	1.524	.021	small
S.11, T.26 N., R.11E. Wilson Creek below concretions	1.495	1.516	.021	small
Scott Co. Glascock Farm S.29, T.28N., R.13E.	1.503	1.524	.021	small
Scott Co. Ellis Farm S.25, T.29N., R.14E.	1.500	1.521	.021	small

[1] All the material here listed is optically negative.

* Data by Grim, Ralph E.: Petrography of the Fuller's Earth Deposits, Olmstead, Illinois, with a Brief Study of Some Non-Illinois Earths. ECON. GEOL., vol. 28, pp. 344–363, 1933.

† Interference figures are too indistinct for exact measurement of optical angle. In better figures it is estimated to be about 10° or 12°.

Montmorillonite.—The optical properties of the Missouri montmorillonite listed in Table I are within the range of the optical properties of the montmorillonite from commercially utilized fuller's earths. This indicates that possibly the Porters Creek formation of Missouri may likewise be utilized as fuller's earth.

The optical properties of the montmorillonite in the upper part of the Porters Creek at Ardeola, Avert, and Zeta are close to those of montmorillonite that comprises the fuller's earth at Olmstead, Illinois. The refractive indices of montmorillonite from the lower 20 or 25 feet of the Ardeola exposure are more like those of the English fuller's earth near Bath. For those seeking fuller's earth for a particular purpose, it would be well to try both the upper and the lower part of the Missouri deposit, for experience [4] has shown that some fuller's earths are better adapted to refining one kind of oil than another.

The refractive indices of the clay mineral from the part of the exposure above the concretions at Wilson Creek (S. 11, T. 26 N., R. 11 E.), from Beech Grove Branch (S. 10, T. 26 N., R. 11 E.), from Poplar Branch (S. 9, T. 26 N., R. 11 E.) and Idalia (S. 28, T. 26 N., R. 11 E.) are higher than those in Table I and indicate that these samples are less likely to be satisfactory as fuller's earth. Although their clay mineral may be montmorillonite with different chemical composition, such as high alkalies, the optical properties are more like those of beidellite ($Al_2O_3.3SiO_2.nH_2O$).

Since the absorption capacity of all the described fuller's earths is believed to be connected with clay minerals of the montmorillonite group, the amount of other minerals present must be considered. Certain beds of the Porters Creek formation in Missouri are at least 95 per cent montmorillonite, and in those examined the total of all minerals besides montmorillonite did not exceed 20 per cent. The minerals that may be present in amounts greater than 1 per cent are quartz, muscovite, glauconite and amorphous silica. These will be discussed briefly.

Quartz.—Unsorted angular quartz grains form about 10 per cent of some parts of the Porters Creek formation in Missouri. The maximum diameter of the grains observed is 0.14 mm., but

[4] Ladoo, R. B.: Non-Metallic Minerals, pp. 231–240. McGraw Hill Book Co., New York, 1925.

Parsons, C. L.: Fuller's Earth. U. S. Bureau of Mines, Bull. 71, 38 pp. 1913.

Porter, J. T.: Properties and Tests of Fuller's Earth. U. S. Geol. Survey, Bull. 315, pp. 268–290, 1906.

the average is nearer 0.05 mm. Large and small grains occur close together with little suggestion of sorting or arrangement in lenses. The angularity of most grains combined with lack of sorting is unusual in a marine deposit and requires explanation. Embayments in quartz like those reported [5] in the Porters Creek formation of Illinois are common in tuffs and bentonite. It seems more likely in the light of the origin advanced later in this paper for the Porters Creek formation that such embayments belong to the earlier volcanic phase rather than indicating a partial replacement of quartz by montmorillonite.

Muscovite.—Muscovite makes up 2 or 3 per cent of the Porters Creek formation. Locally it is concentrated in layers about 1/16 inch thick and causes the bedding to be more pronounced. When these layers are split open, the shiny flakes of muscovite with their flat surfaces arranged parallel to the bedding give one the impression that the layer is nearly all muscovite. However, under the microscope, much montmorillonite can be seen surrounding the muscovite. The muscovite-rich layers alternate at intervals of about one-half inch with clay containing the usual amount of muscovite, so that the average percentage of muscovite for a thickness of 5 or 10 feet does not exceed 5 per cent. An example of this concentration of muscovite is in the bottom part of the exposure near Zeta, where the maximum diameter of the muscovite is 0.24 mm.

In the Porters Creek formation of Illinois it has been suggested that muscovite forms from and alters to montmorillonite.[6] This is unusual for a mineral regarded by most geologists as relatively resistant and the stability of which is attested by its occurrence in the sediments of all periods from Cambrian to Recent. If it is considered in its broader relationship, it is doubtful that any of the Porters Creek muscovite may be considered as having formed from montmorillonite. Muscovite is present in the underlying Cretaceous beds at Ardeola and in the overlying Wilcox formation of Missouri as well as the Lagrange of Illinois. There is no montmorillonite in these formations,

[5] Grim, Ralph E.: *Op. cit.*, p. 350.

[6] Grim, Ralph E.: *Op. cit.*, p. 351.

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[5] Grim, Ralph E.: *Op. cit.*, p. 350.

[6] Grim, Ralph E.: *Op. cit.*, p. 351.

therefore the muscovite in them did not develop from montmorillonite. Furthermore, another source suggests itself. The few grains of kyanite and epidote in the Porters Creek formation indicate some contribution directly or indirectly from a metamorphic rock; probably the muscovite came from the same source.

Glauconite.—The glauconite of the Porters Creek formation of Missouri is strikingly similar to that which occurs in the Olmstead fuller's earth. It forms 1 per cent or less of the total rock and the maximum diameter of the grains is 0.1 mm. The characteristics of both types [7] described in the Illinois earth are exhibited in the Missouri earth. The one with a mottled appearance is a brighter green and appears as rounded grains with the shape of some suggesting molds of foraminifera. The other type with good cleavage is frequently altered to limonite and some grains have properties that agree fairly well with the optical data given for the glauconite in the Olmstead deposit. Textural relationships similar to those interpreted by Grim as evidence that montmorillonite has formed from glauconite are also present.

Amorphous Silica.—Cellular masses of amorphous silica constitute less than 1 per cent of the Porters Creek formation. These are probably diatoms, of which there are two main types. An oval one is more common but slender elongate forms may represent a lanceolate species. The majority of the diatoms are broken, and the contact of the fragments with the surrounding montmorillonite is irregular. A photomicrograph of a complete individual (Fig. 1) liberated by washing the clay shows no indication that it is altering to montmorillonite.

Taliaferro [8] considers that diatomaceous and other associated siliceous sediments are related to volcanism and that volcanic activity was the source of silica for the growth of the organisms. The Porters Creek formation is another case where siliceous organisms occur with volcanic products.

[7] Grim, Ralph E.: *Op. cit.*, p. 351.

[8] Taliaferro, N. L.: The Relation of Volcanism to Diatomaceous and Associated Siliceous Sediments. Univ. Calif. Pub. Bull., Dept. Geol. Sci., vol. 23, pp. 1–56. 1933.

Other Minerals.—Angular or embayed feldspars are next in order of abundance. These were probably derived from several sources and include albite, oligoclase, microcline, and orthoclase. Small euhedral or angular grains of tourmaline, kyanite, epidote, rutile, zircon, and leucoxene are sparsely distributed throughout the Porters Creek formation and together do not total 1 per cent of the rock mass.

Conclusions Based on Mineral Composition.

All the minerals of the fuller's earth at Olmstead, Illinois, are present in the Porters Creek formation of southeastern Missouri. The optical properties of these minerals are remarkably similar and lend support to the stratigraphic evidence that both are of the same age and belong to the same formation. The Porters Creek formation in Illinois is used industrially as a fuller's earth and the continuation of that deposit in southeastern Missouri with similar mineral composition presents promising possibilities that it will prove satisfactory as a fuller's earth.[9]

Origin of the Porters Creek Formation.

In the lower part of the Porters Creek formation at Ardeola there is conclusive evidence that montmorillonite has formed by the alteration of volcanic glass. The characteristic textures of volcanic tuffs have been preserved as well as some of the original glass. The most common relict texture consists in the retention of walls of glass bubbles ranging in diameter from 0.007 mm. to 0.1 mm. (Fig. 2). Single bubbles are most abundant, but there are numerous examples of two or more bubbles joined together. Shards with three curved sides have been altered to montmorillonite (Fig. 3). Slender pumice fragments with the inclosing walls are preserved (Fig. 4) and complete the list of structures that are regarded as unquestionable evidence of volcanic origin. Alteration has apparently been more complete in

[9] Preliminary tests made in the laboratories of the Missouri Geological Survey since this manuscript was prepared indicate that this material is satisfactory as fuller's earth.

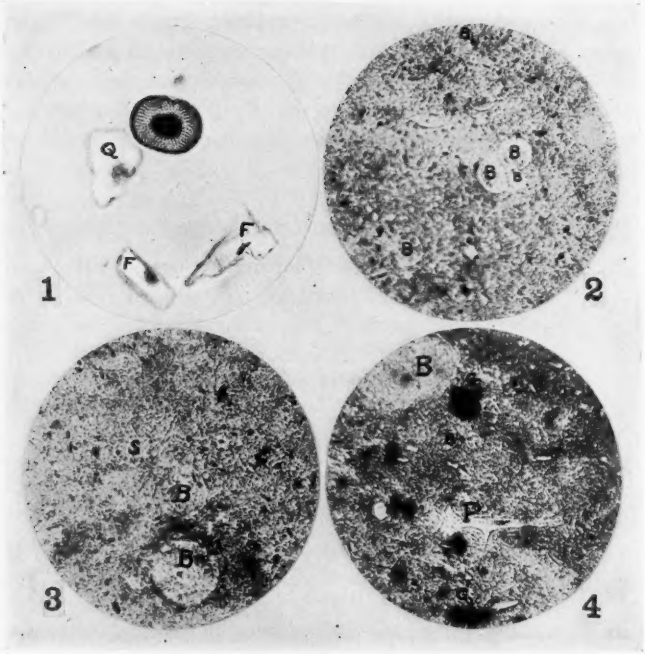

FIG. 1. Diatom with the center obscured by clay of the Porters Creek formation. Angular quartz (Q) and feldspars (F). Scott Co., Mo. $\times$ 130.

FIG. 2. Glass bubbles (B) altered to montmorillonite. Near the center are three bubbles joined together. Porters Creek formation, 12 feet above the Cretaceous-Eocene contact. Ardeola, Mo. $\times$ 130.

FIG. 3. Glass shard (S) with three curved sides and glass bubbles (B) altered to montmorillonite. Porters Creek formation, 12 feet above the Cretaceous-Eocene contact. Ardeola, Mo. $\times$ 130.

FIG. 4. Pumice fragment (P) and bubbles (B) altered to montmorillonite. Large dark areas (G) are glauconite altered to limonite. Porters Creek formation, 12 feet above Cretaceous-Eocene contact. Ardeola, Mo. $\times$ 130.

the upper part of the Porters Creek formation of Missouri and Illinois, and only a suggestion of an occasional bubble, with no volcanic glass, remains. However, the similarity in mineral composition in the upper and lower parts combined with the excellent preservation of relict structures in the lower, removes any doubt that the alteration of volcanic glass was the principal source of montmorillonite. Even if the unproved reactions involved in the change of glauconite, muscovite or other minerals to montmorillonite took place, as has been suggested for the Olmstead deposit, this would provide a very small quantity of montmorillonite.

Deposition of the volcanic products took place in the sea, and detrital minerals, including muscovite, kyanite, epidote, quartz, feldspars and others, were added during accumulation. Conditions were favorable for contemporaneous formation of glauconite and siliceous organisms. A volcanic origin for the deposit offers a satisfactory explanation for all its features, including the embayed quartz and feldspars, and provides a source of silica for the growth of siliceous organisms.

In every respect the Porters Creek formation complies with the accepted definition of bentonite:[10]

> Bentonite is a rock composed essentially of a crystalline claylike mineral formed by devitrification and the accompanying chemical alteration of a glassy igneous material, usually a tuff or volcanic ash; and it often contains variable proportions of accessory crystal grains that were originally phenocrysts in the volcanic glass. . . . The characteristic claylike mineral has a micaceous habit and facile cleavage, high birefringence, and a texture inherited from volcanic tuff or ash, and it is usually the mineral montmorillonite but less often beidellite.

According to this definition, the clays of the Porters Creek formation are bentonite. Based upon commercial usage, clays which have marked ability to remove color from mineral or organic oils are termed fuller's earth. Combining the two concepts, the Olmstead deposit is a bentonitic fuller's earth and the

[10] Ross, Clarence S. and Shannon, Earl V.: The Minerals of Bentonite and Related Clays and Their Physical Properties. Amer. Cer. Soc. Jour., vol. 9, p. 79, 1926.

continuation of this deposit into Missouri with similar composition suggests its use as a fuller's earth. Bentonitic fuller's earths include some of the most excellent fuller's earths.[11]

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[11] Ross, C. S., and Shannon, E. V.: *Op. cit.*, pp. 77–96.
Kerr, Paul F.: *Op. cit.*, pp. 192–198.
Grim, Ralph E.: *Op. cit.*, pp. 344–363.
Broughton, M. N.: *Op. cit.*, pp. 135–140.

DISCUSSION AND COMMUNICATIONS

TRANSPORTATION OF GOLD BY ORGANIC SOLUTIONS.

Sir: Based on laboratory experiments and observations in the field, Dr. F. W. Freise has found that aqueous humic acid suspensions take gold into solution and transport it in the absence of oxygen and electrolytes.[1] In his experiments, specimens of gold plates and dusts, ranging from pure gold to 600 fine, lost weight after being exposed to humic acids extracted from lignite taken from the vicinity of Carangola, Minas Geraes. The amount of weight lost increased with the concentration of the humic acid sol, and the duration of the experiment. This was determined experimentally and, upon further field experiments and observations on depleted placers which are thought to have been rejuvenated in this manner, was accepted as an occurrence under natural conditions.

Water from a stream high in humus was made to flow through a flume, forty-five feet long, packed evenly with sands, clays, and kaolin, together with gold dust in the upper one tenth of the flume. At intervals of 10, 20, 30, 40, 50, and 60 days, samples were taken at definite points along the length of the flume and tested for gold. From these tests it was found that gold was transported by the stream. According to Freise, the gold was transported chemically, presumably as a humate.[2]

Since the solution, either colloidal or true solution, of gold by humic acids, has been heretofore unknown, experiments were carried out by the writer, upon the suggestion of Dr. W. H.

[1] Freise, F. W.: The Transportation of Gold by Organic Underground Solutions. ECON. GEOL., vol. 26, pp. 421–31, 1931.
Freise, F. W.: Metall und Erz., vol. 27, pp. 442–5, 1930.

[2] Freise, F. W., ECON. GEOL., vol. 26, p. 429, 1931.

Emmons, to throw further light upon the phenomenon. In these experiments the lyophilic hydrosol of humic acids was separated from lignite and peat by the same procedure followed in Freise's original tests.[3] The lignite used was from the mines of the Lehigh Briquetting Company at Lehigh, North Dakota, and the peat was from various peat bogs near Minneapolis and St. Paul, Minnesota.

The humic acids were precipitated by adding HCl to a liquor obtained by digesting the lignite or peat with a KOH solution. According to Stack this variety should be modified in name to "meta humic acids" which include only those that are soluble in cold KOH.[4]

Some of the electrolyte causing the flocculation was removed by repeatedly adding airless distilled water, allowing the humic acids to settle in airtight flasks, and then decanting the supernatant liquid, until the humic acids became peptized. To remove more of the electrolyte, the dispersion medium and additional wash waters were separated from the humic acids by a filter. No amount of washing can remove the last traces of adsorbed electrolyte, so for some of the experiments still more of the adsorbed ions were removed by dialysis through a cellulose membrane. There are methods of preparation of humic acid in which the effects of the alkali are minimized, but they were not used because it was desired to maintain uniformity in duplicating Freise's experiments.

The concentration of the dispersed humic acid sols prepared for the solution of gold ranged from 0.1 to 5.0 per cent. of humic acid determined on an unsolvated (dry) basis.[5] These are a deep dark brown, and much thicker and more viscous than humus-bearing sols ordinarily found in nature.

[3] Semek, Britislav G.: Neue Forschungsergebnisse in der Chemie der natürlichen Humensauren. Brennstoff Chemie, vol. 9, p. 381, 1928.

[4] Stack, Hans: Zeit. Angew. Chem., 44, pp. 118–20, 1931.

[5] Per cent. conc. $= \frac{\text{wt. of dehydrated sol in 10 cc. disperse system} \times 100}{\text{wt. of 10 cc. disperse system}}$

Ten cubic centimeters of each sol were set aside, evaporated to the denaturized condition, and weighed, to determine the per cent. concentration of humic acid used. A concentration determined on a solvated basis would be meaningless, as the quantity of adsorbed water cannot be measured.

For each solubility experiment, 250 cc. of the sol were used, and between 3 and 5 grams of gold, which was weighed to the nearest 0.1 of a milligram before and after being subjected to the colloidal humic acid for periods ranging from 24 to 400 hours, and more for individual experiments.

Three finenesses of gold were used: pure gold; 70 per cent. Au and 30 per cent. Ag; and 45 per cent. Au and 55 per cent. Cu. They were all in the form of sheets having surface areas of from 40 to 110 square centimeters for each experiment.

The solutions were not subjected to motion except for the gentle circulation produced by the nitrogen passing through the liquids in some of the experiments. To avoid the possible danger of occlusion by the humic acid micells, flotation effects at the liquid-colloid interfaces, and loss in handling, only sheets of gold were used in preference to fine particles (.005 mm. to .002 mm.) as used by Freise in some cases.

Freise's tabulations show one experiment in which 0.91 per cent. of 0.01 inch gold plate weighing about 1.7 grams was lost in 48 hours in a 0.1 per cent. suspension. This amount of plate would have an area of approximately 7.2 cm^2, and the amount of gold dissolved would be 2.1 mg. per cm^2, thus proving that excessively fine gold was not necessary to obtain sufficient surface for a detectable loss.

In the writer's laboratory, gold plates of only one fineness were placed in each flask, thus avoiding possible galvanic effects. In some instances strained gold plates were utilized; in others the gold was annealed. The work was carried out at room temperatures.

In the first experiments using the above materials the humic acids, peptized in airless distilled water, were placed with a weighed amount of gold in each flask and immediately sealed with rubber stoppers. Even in the most concentrated sol and after 400 hours there was no loss in the weight of the gold. For additional precaution the stoppered end of some of the flasks was dipped in sealing wax. As anticipated, this had no influence on the results.

Next a series of tests were performed in which the colloidal suspension was prepared as before, but during the time the gold was in contact with the humic acid, nitrogen was continually bubbled through the sol to wash it free of traces of oxygen. Still no gold was dissolved.

In some instances freshly precipitated humic acids were used, as it is well known that some of the properties of lyophilic colloids may depend on their history. In other experiments the acids were deliberately allowed to age and become somewhat gelatinous. A total of seventy-five individual experiments were carried out, but even under the conditions which Freise states are favorable—the exclusion of oxygen, a minimum amount of electrolyte, highly concentrated humic acid sols and long duration of the tests—no gold was dissolved.

As a further check, some of the humic acid sols, after being in contact with the gold, were tested for any dissolved gold by evaporating the humic acid to dryness and igniting the organic matter. The incombustible residue was then dissolved in a few drops of aqua regia and diluted with a few cubic centimeters of water. This was then slightly heated with a solution of stannous chloride containing a little stannic chloride, but even the faintest purple of Cassius, the characteristic color which is obtained when testing for gold in this way, did not appear in any of the tests, although by using this test, it is said to be possible to detect one part of gold in 600,000 parts of solution.

The gold after being removed from the humic acid appeared unaltered under the microscope, with the exception of one or two areas of an exceedingly thin brown film, each covering about four square millimeters, which may have been the beginning of a deposition of an iron humate film similar to the incrustation on gold described by Freise.

In investigating the behavior of humic acid toward auric gold, the writer shook dried humic acid with distilled water, thus producing an orange-yellow liquid. To this solution a small amount of auric chloride solution was added. Upon slightly heating, black amorphous gold was readily precipitated, the humic acid effecting a reduction of the auric gold.

Small gold flakes were subjected to the same type of humic solution for seven months. Then the solution was evaporated and the ignited residue was tested for gold by the purple of Cassius procedure, which gave negative results.

It is difficult to account for the action of any known humic acid as a solvent for a substance as inactive as gold, although it may possibly be that this property is dependent upon the quality of the vegetation, the conditions during humification, or the presence of adsorbed or chemically combined impurities. For example:—In its higher valence states, manganese oxide, commonly occurring in bogs, would tend to react with the ionic chlorine of the hydrochloric acid that is used as a precipitant for the humic acid—provided the chlorine ion remained not completely washed out. Thus nascent chlorine might be formed, which is a ready solvent of gold.[6] It is also likely that in the presence of KCl or other chlorine salts in nature, as well as in the laboratory, a certain amount of free HCl would be liberated by hydrolytic adsorption of the salts by colloidal humic acid.[7]

The reaction between humic acid and gold may be regarded as oxidation when one considers that a gold atom would have to lose either one or three valence electrons in order to combine as a humate. It is a significant fact that by its position in the electrochemical or activity series, gold tends to retain its normal number of electrons tenaciously. Therefore, it is difficult to understand this paradox that humic acid, a reducing agent, could oxidize gold.

In the laboratory a high humic acid concentration which seldom, if ever, occurs in nature can be attained. The detrimental effects can be minimized. These are principally dissolved oxygen and electrolytes, especially the carbonates, and bicarbonates, and then sulphates, bisulphates, and nitrates, and last in order come the chlorides, which Freise states have little effect. The only added impurities introduced in the laboratory are potassium and

[6] Emmons, W. H.: Trans. Am. Inst. Min. Eng., vol. 40, pp. 767–838, 1910.

[7] Ganguli, A.: The Hydrolytic Adsorption by Humic Acid. Phil. Mag., vol. 7, p. 317, 1929.

chlorine ions in amounts small enough to permit deflocculation of the humic acid, but according to Freise the chlorine ion is not adverse to solution of gold.

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DIATOMACEOUS EARTH IN OREGON.

Sir:—In his discussion of my paper under the above heading (this Journal, Dec., 1932), Mr. V. L. Eardley-Wilmot (this Journal, Jan., 1934) has taken exception to some statements of mine. In the first place he questions the use of the term, "diatomaceous earth." As this term has long appeared in American geological literature, I do not think this point needs further mention.

The vital point in his discussion seems to be the specific gravity of the diatomite. And in inferring an error in Wilmot's figures I doubtless have made a mistake, inasmuch as the pure substance apparently has the specific gravity given by him. However, if one is considering the diatomaceous material as it actually exists, with a certain amount of pore space filled with air, the specific gravity of this material depends upon its physical structure, and because of this particular physical structure, with the high percentage of voids, the specific gravity of the pure substance would not throw much light upon its actual condition. This material has its value and use in industry because of its peculiar physical condition, and not because of the specific gravity of the pure substance excluding the air. In looking through the literature, I note that specific gravities for this kind of material vary from .45 up to that of the pure substance.

With reference to the meaning of the remark at the bottom of page 709, there has been a mistake in the preparation of the manuscript which was overlooked in the proof. That part of the sentence which reads "and a 34.6 per cent. increase in the addition of 10 per cent. diatomaceous earth" should follow the sentence

at the top of page 715 referring to the Smith-Emery Company tests.

As for the displacements in the deposits, I did see a number of local slumps, but in my article I had in mind displacements of a more regional character. However, I may easily have overlooked something Mr. Wilmot noted.

I wish to thank Mr. Wilmot for his mention of these points, as I am as anxious as he is to avoid inaccuracies or important omissions in my statements concerning these deposits.

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REVIEWS

The Sky Determines: An Interpretation of the Southwest. By Ross Calvin. Pp. 354, pl. 12. The Macmillan Co., N. Y., 1934. Price, $2.50.

To anyone who loves the American desert, to him who fears it, and to the many who are unfamiliar with its character, but who wish to know something about its aspect, and romantic history, The Sky Determines will prove fascinating reading. Its theme is that the sky, the source of moisture and of desert-making heat, not only determined the peculiar climatic and topographic features of New Mexico but its culture and economic development as well. "It is no accident," writes the author, "that in New Mexico plant life is generally grotesque in appearance; that prehistoric man here attained a level of culture elsewhere unequalled within the boundaries of our country; that to-day Indian life persists unchanged here long after it has disappeared in other parts." Sky determined the mode of life of forgotten peoples, of the Pueblo-dwellers, the Mexicans and the Apaches. It determined the dominance of the ranchmen until recent years and was the cause of the failure of the Conquistadores to make good their early conquests.

Beginning with a general account of the climate of the desert State and descriptions of the desert and its inhabitants, of the mountains and their forests and the part they play in the State's economy, the volume continues with colorful discussions of its ancient peoples, of the Conquistadores and their activities in attempting to conquer its inhabitants and christianize them, of the Puebleños, or modern Pueblo-dwellers, of the Mexicans, or modern descendants of the crossing of Spaniards and Indians, and of the brave and warlike Apaches, representing the "supreme example of the adaptation of man to an arid environment," and concludes with the thesis that the ranchmen were the only type of agriculturists that could have existed under the tyranny of the sun previous to the discovery and development of underground water supplies.

The author must know New Mexico intimately, for he interweaves in a pleasing way descriptions of many significant incidents during its history, descriptions of its topography, and characterizations of its many types of inhabitants. The chapters on the Conquistadores, the Puebleños and the Apaches, all of which are well written in a poetic strain, are particularly interesting reading. As a whole, the volume furnishes a

striking picture of the romantic history and remarkably devious development of a State in which environmental conditions are especially unfavorable to settlement along normal lines. It is well worth reading.

W. S. BAYLEY.

Lehrbuch der Erzmikroskopie, Volume I, Part I. By HANS SCHNEIDERHÖHN AND PAUL RAMDOHR. Pp. 312, figs. 145, two colored plates. Gebrüder Borntraeger, Berlin, 1934. Price (unbound) 24 M.

This book should logically have preceded volume II (reviewed in ECON. GEOL., vol. 27, p. 97, 1932), since it contains the descriptions of the methods employed in the determination of the minerals discussed in Volume II. According to the preface, this part of Volume I is almost entirely Schneiderhöhn's. About 20 pages about the theory of optical behavior of opaque minerals in reflected light is by M. Berek. Another section dealing with the photoelectric cell is by Ehrenberg and Ramdohr, and a third is by Doris Korn. This is the 10th and last chapter and presents in a simple way the newly developed method of determining the optical orientation of an opaque mineral in a polished section. It fills the long felt need of such a discussion, although it must of necessity be rather theoretical.

One is not sure whether this book is intended for a text or for a reference work. Schneiderhöhn's style becomes too pedantic in places to please the student and too little credit seems to be given to the work done in other laboratories. This, however, is the only criticism of this otherwise excellent volume. The first chapter deals with the history and general application of "ore microscopy." The second covers 50 pages and describes the optical and illuminating apparatus for examinations in reflected light. Most authors would have made this chapter half as long. The third chapter gives highly detailed instructions for the polishing of specimens. Then follow ten pages (Chapter IV) of photomicrography. In the fifth chapter some of the physical properties, such as hardness, relief, cleavage visible in polished sections, electrical conductivity and magnetism are discussed. The sixth chapter is the most extensive (67 pages) and at the same time the most original. It treats of the theory and application of ordinary and polarized light and its qualitative and quantitative measurements. Too little of this has been applied by American investigators. The question may be asked here whether the ore geologist, who really gave the impetus to mineralography, will be willing and able to use such highly specialized methods as photometry, etc. Perhaps the day is not far distant when one mineralographer will specialize in sulphosalts of silver and another in tellurides of it. This section is so specialized that a physicist will understand it more readily than an economic geologist.

The seventh and eighth chapters deal more with the methods which

have been in general use so far by mineralographers. The microchemical tests and etch methods are ably discussed, though Schneiderhöhn again emphasizes the inadequacy of chemical reactions as a means of identification. His chapter on etching for microstructures is very instructive and interesting. A short chapter (IX) deals with the measuring of grains in polished sections.

No doubt it took many years of the most painstaking work to produce this excellent volume. The book is apparently practically free from errors of any kind. It is printed on good paper and the illustrations are excellent, especially the two colored plates which were reproduced from "Agfa-color Film." The reviewer thinks it unfortunate that the promised Part II of this volume could not have been combined with it. Since it is to contain the genetic relations of the minerals to one another and to ore deposits, it should have helped the sale and distribution of Part I.

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Tertiary Faunas. A Text-book for Oilfield Paleontologists and Students of Geology. Vol. II. **The Sequence of Tertiary Faunas.** By A. M. DAVIES. Pp. x + 252, figs. 28, pl. 1. Thomas Murby and Company, London, 1934. Price 15 s.

This volume, based on lectures to students of oil technology in the Royal School of Mines, London, is intended to supply a reference book for those interested in the distribution of fossil forms in the various faunal provinces of the world, more particularly in those characterizing the Tertiary faunas in provinces that have become oil-bearing. The first two chapters, comprising 60 pages, deal with the present distribution of animal life, and the geological interpretation of fossils. The next two chapters are devoted to descriptions of the faunas of Early and of Later Tertiary time as exhibited, so far as known, in the various provinces and basins throughout the World, and their relations to one another. A selected bibliography of Early Tertiary faunas contains 173 entries and one of Later Tertiary faunas, 124 entries. A comprehensive index of localities, genera, etc., concludes the volume.

The book is in general a summary of the work done on the subject by the paleontologists who have studied most intensively the faunas of the different districts discussed, and comments by the author on their conclusions. Volume I, which will appear before the end of the year, will treat the faunas systematically. In his Preface the author states that the present volume "should be readable by itself to any student with a general knowledge of paleontology, though he might have to await the appearance of the first volume to learn the particular characters of some of the fossils mentioned."

W. S. BAYLEY.

BOOKS RECEIVED.

DAVID GALLAGHER.

Stratigraphy of Western Newfoundland. C. SCHUCHERT AND C. O. DUNBAR. Pp. 122, pls. 11, figs. 8. Geol. Soc. America, Mem. 1. Washington, 1934. The result of many years of study in this stratigraphically critical region. The first of the Society's series of Memoirs made possible through the bequest of the late R. A. F. Penrose, Jr.

Beach Placers of the Oregon Coast. J. T. PARDEE. Pp. 41, figs. 16. U. S. Geol. Surv., Circ. 8. Washington, 1934.

Geology and Ore Deposits of the Elk City, Orogrande, Buffalo Hump, and Tenmile Districts, Idaho County, Idaho. P. J. SHENON AND J. C. REED. Pp. 89, pl. 1, figs. 14. U. S. Geol. Surv., Circ. 9. Washington, 1934. Gold lodes and placers.

Geotechnische Karte der Schweiz. P. NIGGLI AND F. DE QUERVAIN. Comm. Géotech. de la Soc. Helvétique des Sci. Nat. Kümmerly & Frey, Bern, 1934. Geological map in colors, with contour interval 100 meters, scale 1:200,000, size about 2 x 3 ft. Accompanied by explanatory booklet in French and German. This is the first, and northwestern, one of four sheets to cover all Switzerland.

Quebec Bureau of Mines, Ann. Rpt. 1932, Pt. B. Quebec, 1933. Three papers: Mining properties of Pascalis-Louvicourt area, L. V. BELL, pp. 59, pls. 3, figs. 9, map; Assup River map-area, and prospects in Vauquelin and Tiblemont townships, A. M. BELL, pp. 33, fig. 1, map; Granitic gneisses in the Foch area, Abitibi, L. V. BELL, pp. 10, pls. 1, map.

Oil and Gas Production North of Sebree in Henderson and Webster Counties, Kentucky. W. L. RUSSELL. Pp. 3, pls. 2. Ky. Bur. Min. and Topog. Surv., Bull. 4. Univ. of Ky., Lexington, 1934.

Oil and Gas Pools of Hart County, Kentucky, W. L. RUSSELL. **Structure Maps of the LeGrande Pool and Logsdon Valley Pool,** J. H. MCCLURKIN. Pp. 14, figs. 3. Ky. Bur. Min. and Topog. Surv., Bull. 5. Univ. of Ky., Lexington, 1934.

Geology of the Dargaville-Rodney Subdivision, Hokianga and Kaipara Divisions, New Zealand. H. T. FARRAR. Pp. 86, pls. 5, geol. maps 19. New Zealand Geol. Surv. Bull. 34. Wellington, 1934. 17 s. Area of Mesozoic and Cenozoic sedimentary and igneous rocks.

Investigations in Ore Dressing and Metallurgy. W. B. TIMM *et al.* Pp. 287. Canada Dept. Mines, Mines Branch, No. 736. Ottawa, 1934. Contains many short reports.

Lehrbuch der angewandten Geophysik. H. HAALCK. Pp. 376, pls. 6, figs. 142. Gebrüder Borntraeger, Berlin, 1934. 26 RM.

Copies of books mentioned under "Reviews" or under our "New Book List" (see advertisement page) may be purchased through our Journal Bookshop by writing to W. S. Bayley, University of Illinois, Urbana, Ill.

SCIENTIFIC NOTES AND NEWS

Ira B. Joralemon has recently been on an airplane trip to Alaska to examine mines and unexplored regions north of the Arctic Circle.

Bailey Willis has been elected president of the Pacific Division, American Association for the Advancement of Science.

Scott Turner's resignation as Director of the Bureau of Mines was accepted by the President on August 15. His address is now Room 801 Otis Building, 810 18th Street, N.W., Washington, D. C.

Anton Gray, who returned to London recently after a trip to South America, is now in the United States.

Sydney H. Ball has been spending some weeks in Ontario and British Columbia on professional business.

Arthur D. Storke, director of Rhodesian Selection Trust, Roan Antelope, and Mufulira Copper, returned to London from South Africa in July.

Edward Sampson, professor of geology at Princeton University, is now chairman of the Department, the former chairman, A. H. Phillips, remaining as special lecturer.

Otto Sussman is on a trip to East Africa and the Northern Rhodesia copper mines.

A. H. Koschmann was in charge of a party lately sent out by the U. S. Geological Survey to explore the mineral deposits in the Ketchikan district, Alaska.

F. C. C. Lynch is at the head of the recently organized Bureau of Economic Geology at Ottawa, Canada, which has taken over some of the work of the Geological Survey.

The Kansas Geological Society held its Eighth Annual Field Conference from August 31 to September 4, going from Lamar, Colo., to Twin Buttes, Purgatoire Dome, Cimarron Valley, and Mt. Capulin, across the Panhandle of Oklahoma to Belvidere, Kansas.

William A. P. Graham, associate professor of Geology at Ohio State University since 1928, died on August 11, aged thirty-five. He had been engaged in geological work in the Sweet Grass Hills in northern Montana, and was found dead in bed.